SEE
FOLLOWING
NOTE

PARTS OF THE ORIGINAL DOCUMENT

ARE OF POOR REPRODUCTIVE QUALITY

CERTAINES PARTIES DU DOCUMENT ORIGINAL

SONT DE PIÈTRE QUALITÉ DE REPRODUCTION

CONTRACT SERIAL NUMBER 79045-01-SS
DSS REQUISITION NUMBER 23440-7-9045
CONTRACTOR: MCGILL UNIVERSITY

FINAL PROGRESS REPORT

FLAMMABILITY LIMITS AND QUENCHING OF DUST-AIR FLAMES

by

R. Knystautas
J.H. Lee

McGill University, Montreal, Quebec

May 1988

MICROMEDIA

205 pp

FINAL PROGRESS REPORT

FLAMMABILITY LIMITS AND QUENCHING OF DUST-AIR FLAMES

by

R. Knystautas
J.H. Lee

Submitted to

Dr. K.J. Mintz
Energy, Mines and Resources, Canada
CANMET, MRL

205

McGill University,
Montreal, Quebec

May 1988

PREFACE

The present report describes the current state of progress of ongoing research on dust combustion in the Mechanical Engineering Department of McGill University, Montreal. In 1987-88, a substantial part of this activity was sponsored by EMR under contract 23440-7-9045 so that the research has been predominantly directed to respond to the contractual requirements. The specific work statement in the EMR contract requests us to determine, within the existing experimental capabilities, the i) quenching distance for dust flames, including the effect of particle size of coal dust and the type of coal, and the ii) lower flammability limits of three Canadian coals under constant pressure. Under item ii), three samples of Canadian coal were to have been supplied to us through the auspisces of EMR. In the end only two coal dusts were received by us in fine dust form. The third coal sample was shipped to us in the form of coarse fragements (~ 1 *cm* lumps). We therefore could not obtain any flammability limit or quenching distance data for the third coal sample.

To be able to carry out a systematic and meaningful analysis of the data, our approach has been to carry out a broad flammability study relating the results achieved to well-established benchmark data in the field and in our previous studies with other particulate materials. To this end it was essential first to carry out constant volume flammability limit studies to place the Canadian coal dust supplied by EMR in the framework of other organic dusts including coal dust for comparison on a relative basis. The results of this study are reported in the first part of the report. Once the relative flammability assessment was achieved under constant volume conditions, the more difficult constant pressure measurements were undertaken and the results are reported in the second part of the report. Finally, to complete the report, the Appendices are included which contain the recently published works that are a direct result of the continuing EMR sponsorship of dust combustion research at McGill University over the past several years.

RESUMÉ

Les limites d'inflammabilité des poussières de charbon canadien ont été mesurées à volume constant et à pressions constante. Les poussières de charbon canadien étudiées sont celles due Cap Breton, de taille 325, et celles de Colombie Britannique, de taille non précisée. Elles nous sont fournies par l'E.M.R. L'étude demandée, dans le cadre du contrat, consiste à mesurer les limites d'inflammabilité à pression constante ainsi que la distance d'extinction à pression constante. Afin de pouvoir comparer les conditions d'inflammabilité des poussières de charbon à celles de matériaux organiques bien connus, des essais de combustion à volume constant ont été tout d'abord entrepris. Ceci a été réalisé dans un réservoir cylindrique de type Hartmann d'un volume de 180 litres. On a trouvé, pour les échantillons de poussières de charbon du Cap Breton (taille 325 et diamètre $< 44\mu m$), une limite inférieure d'inflammabilité de $40 g/m^3$, ce qui est identique à la limite inférieure d'inflammabilité précédemment déterminée pour les poussières de charbon Devco 26 (taille 200 et diamètre $< 74\mu m$). Les échantillons de poussières de Colombie Britannique, de taille non spécifiée, ont une limite inférieure d'inflammabilité de $150 g/m^3$. Les expériences à pression constante ont été réalisées dans le tube de combustion vertical, utilisé auparavant pour de études d'extinction de la combustion de poussières. Les poussières des deux charbons canadiens ne peuvent s'enflammer et entretenu la propagation d'une flamme dans le tube vertical, dans des conditions de pression constante. Ceci signifie que la distance d'extinction pour ces deux charbons est supérieure à $190 mm$ qui est la dimension transversale (diamètre) du tube. Puisqu'on a trouvé, avec les poussières de charbon du Cap Breton, la même limite d'inflammabilité à volume contant qu'avec les poussières de charbon Devco 26 qui avaient aussi une distance d'extinction supérieure à $190 mm$, les résultats obtenus ne sont pas surprenants. Les poussières de charbon de Colombie Britannique sont beaucoup moins inflammables que celles du Cap Breton ou celles du charbon Devco 26.

SUMMARY

Flammabiity limits of two Canadian coal dusts have been measured under constant volume and constant pressure combustion conditions. The Canadian coal dusts are the Cape Breton mesh 325 and the British Columbia of unspecified size supplied to us through the auspices of EMR. The contractual requirement is to measure the constant pressure flammability limits and the quenching distance at constant pressure. To put the two coal dusts in perspective relative to flammability of well established organic materials, constant volume combustion tests were carried out first. This was done in a Hartmann-type 180 litre cylindrical vessel. The Cape Breton coal dust sample (325 mesh, $< 44\mu m$) was found to have a lean flammability limit of $40gm/m^3$ which is identical to the previously measured lean flammability limit for Devco 26 coal dust (200 mesh, $< 74\mu m$). The British Columbia coal dust sample of unspecified size had a lean flammability limit of $150gm/m^3$. The experiments at constant pressure were carried out in our vertical combustion tube facility used earlier in dust combustion quenching tests. The Canadian coal dusts could not be ignited to sustain flame propagation in the vertical flame tube under constant pressure conditions. This indicates that the quenching distance for both coals is in excess of $190mm$, which is the transverse dimension of the flame tube. Since the Cape Breton coal dust was found to have identical flammability limits at constant volume to the Devco 26 coal dust, which also had a quenching distance in excess of $190mm$, the results are not surprising. The British Columbia coal dust is much less flammable than either the Cape Breton or the Devco 26 coal dusts.

PART I

LEAN FLAMMABILITY LIMITS OF COAL DUST UNDER CONSTANT VOLUME COMBUSTION

by

R. Knystautas
J.H. Lee

McGill University
Montreal, Quebec

May 1988

1. INTRODUCTION

The minimum level of dust concentration, suspended in a dust-air mixture, that can be ignited and sustain combustion is generally referred to as the lean flammability limit. It obviously is of great practical importance such as for example to assess the fire and explosion hazard of volatile dusts in the mining and industrial environments. Unfortunately, the lean flammability limit of a dust-air mixture cannot be defined solely as a fundamental property of the dust-air medium itself. Rather it depends strongly on the apparatus, the boundary conditions under which the flammability tests are performed and on the chosen flammability criterion.

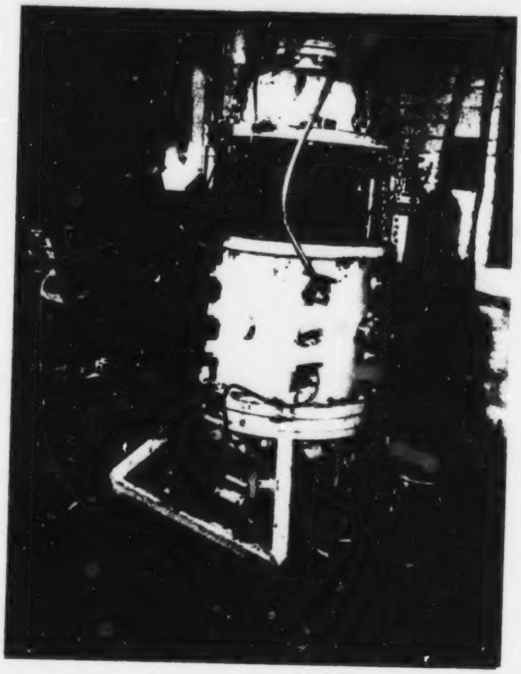
In spite of these limitations and in view of practical necessity, extensive measurements of the lean flammability limits of many volatile dusts have, nevertheless, been carried out over the years(1). Most of these measurements have been made in specific confined pressure vessels under constant volume conditions. The earliest measurements were derived from tests in the Hartmann bomb, which was a "standard" 1.23 litre cylindrical vessel used extensively for dust explosibility tests(2–5). As of about a decade ago the Hartmann bomb was replaced by, first, an 8 litre vessel at the US Bureau of Mines(6–8) but currently the 20 litre(9–11) and 1 m^3(12) vessels are considered the minimum norm for dust explosion studies. The reasons for abandoning the original Hartmann apparatus are numerous. Among the most serious is that the results are non-representative in that they could not be correlated from laboratory to laboratory and could not be scaled to results in larger vessels. This is most likely due to the non-uniform dispersion, wall effects and of necessity, a weak ignition source. The 20 litre vessel is now considered the minimum scale which is able to simulate full-scale dust combustion scenarios(12,13).

As a result of EMR sponsorship, we have had at McGill University since about 1983, an 180 litre dust explosion vessel of the Hartmann type. Extensive tests on the explosibility of a variety of dust-air mixtures including hybrid mixtures(14) have been carried out in this facility in the past five years. To assess the relative flammability of the two Canadian coal dusts supplied to us by EMR, the 180-litre test vessel was reactivated in 1987 to generate the benchmark flammability data for these dusts.

2. EXPERIMENTAL DETAILS

The apparatus used for flammability limit tests at constant volume for the Canadian coal dusts has a volume of 180 litres and is cylindrical in shape with rounded dome-shaped ends. The cylinder itself consists of a straight portion (48.2 *cm* in diameter by 54.2 *cm* long) capped by two dome-shaped ends that are each 48.2 *cm* in diameter, with a mean equivalent cylindrical length of approximately 22 *cm* each. An overall view of the apparatus is illustrated in the photograph below and schematically in Fig. 1.

The dust is deposited in a circular concave cup and placed at the bottom of the vessel. The dust is then dispersed with an air blast from an external 1 litre vessel pressurized to 1.5 *MPa*. Ignition is achieved centrally via a pyrotechnic electric match composed of a thin glow wire wrapped with 1.2 *gm* of black gun powder. Diagnostics were composed solely of pressure time history measurement in the explosion vessel via a PCB 113A24 piezoelectric transducer ($\sim 5\ mv/psi$ sensitivity). A solid state time delay generator was used to vary the time interval between dispersion and



PHOTOGRAPH OF THE 180-LITRE CYLINDRICAL EXPLOSION VESSEL

ignition. All tests were carried out at an initial air pressure of one atmosphere. The criterion for flammability was set as an overpressure of 20.7 kPa above the vessel pressure after dispersion. This value was chosen because it corresponds to the overpressure generated by a quiescent mixture of 4.0% hydrogen in air in the present apparatus. The 4.0% H_2-air composition is the lean upward propagation limit for hydrogen in air as reported by Coward and Jones(15) and Hertzberg(16). Similar pressures were also obtained for the limit mixture of 5.0% methane-air(14,15). All the raw experimental data from this experiment are appended at the end of this section of the report.

3. RESULTS AND DISCUSSION

The dispersion of dust into the 180 litre cylindrical vessel takes a finite amount of time to achieve an optimum uniform dust distribution for a given nominal dust concentration. One of the first questions to be answered is what is this optimal time at which point the dust-air mixture should be ignited. To answer this type of question and to check out the apparatus and diagnostic techniques, a test dust was first used in preliminary experiments. The test dust was commercial cornstarch. The reason for the choice of this particular test dust was that it is readily available as a consumer product, its properties are relatively well-known from previous studies(14,17) (eg. mean particle size $\sim$ 15 μm) and it is an easily ignitable dust in low concentrations. A systematic set of preliminary experiments were carried out to determine the lean flammability limits of cornstarch dust-air mixtures. In particular, the tests were aimed at establishing the optimum time between dispersion and ignition, to check out the operational procedure of running the dust explosion tests and to assess the applicability of the flammability limit criterion under actual test conditions. The test results for cornstarch dust-air mixtures as a function of ignition delay time were extracted from oscilloscope pressure records appended to this report. The results are displayed numerically in Tables 10 through 14. Ignition time delays from 100 to 600 *msec* were used. The tabulated results show the maximum pressure rise and the maximum rate of pressure rise in a given nominal dust-air mixture at a particular ignition delay. If one plots the $(\Delta p)_{max}$ and $(dp/dt)_{max}$ at a given ignition delay as a function of nominal dust concentration, then typical trends are illustrated for cornstarch dust-air mixtures in Figs. 2 and 3, respectively. If one looks at $(\Delta p)_{max}$ vs concentration in Fig. 2 then one sees that $(\Delta p)_{max}$ increases with increasing dust concentration. The trend is identical to that observed by Hertzberg et al(7) in their study of pulverized coal dust flammability limits (see their Fig. 2 in Ref. 7). The change of slope in the curve at the flammability limit criterion (i.e. $(\Delta p)_{max} \simeq 3\ psig$ (20.7 kPa)) is clearly evident just as it is in the Hertzberg et al results. If the flammability limit results are determined in this way for the different delay to ignition times in our experiments, then the results for cornstarch are shown on the left in Table 15. Note that the curve for $(dp/dt)_{max}$ at the flammability limit (Fig. 3) also shows a distinct change of slope. Recall, however, that the criterion for the flammability limit is based on $(\Delta p)_{max}$ and not on $(dp/dt)_{max}$. The flammability limits for cornstarch dust-air as determined in this way as a function of ignition delay time (Table 15) clearly show that the minimal dust concentration corresponds to ignition delay time of the order of 100 – 200 *msec* which is now taken as the optimal dust suspension environment. The absolute value of the flammability limit concentration for cornstarch dust-air mixtures is 75 gm/m^3. These results are compared in Table 16 with flammability limit data measured in the Hartmann bomb and the 5 m^3 explosion vessel. The Hartmann bomb results can, of course, be dismissed immediately for reasons explained earlier. The good agreement beween the 180 litre vessel results and the 5 m^3 results is to be noted.

Tables 1 to 6 show the results in numerical form for combustion of the Cape Breton coal dust (specified 325 mesh, $< 44\ \mu m$) for different ignition delay times ranging from 100 to 600 *msec*. Figs. 4 and 5 show the typical $(\Delta p)_{max}$ and $(dp/dt)_{max}$ as a function of concentration, taken arbitrarily at an ignition delay time of 200 *msec*. The change of slope at the flammability limit criterion is identical and unmistakably evident as in the cornstarch case and in Hertzberg et al(7) results. Table 15 indicates that the optimal dust suspension condition corresponds to an ignition delay time of 100 *msec*. For this condition, the flammability limit result is 40 gm/m^3 which makes this coal similar to the Devco 26 coal dust (200 mesh, $< 74\ \mu m$) tested by us earlier(18). The results for flammability limits at constant volume for different coal dusts are compared in Table 17. Note that the Cape Breton coal dust and the Devco 26 coal dust have the lowest flammability limit dust concentrations of the available results for the different variety of coals. Again note the inflection in the curve for $(dp/dt)_{max}$ at the flammability limit for the Cape Breton coal (Fig. 5).

We have no particle size specification for the second sample of coal dust supplied to us through EMR, which is the British Columbia coal dust. The constant volume combustion results for this coal dust are displayed numerically in Tables 7 through 9. Ignition for this coal dust could only be achieved with a 100 *msec* delay regardless of dust concentration or even drying. From Fig. 6 it is evident that the flammability limit is 150 gm/m^3. The curve for $(\Delta p)_{max}$ as a function of concentration does not, however, rise as steeply as the Cape Breton coal dust nor is there as pronounced a change of slope at the flammability limit. Fig. 7 shows the corresponding curve for $(dp/dt)_{max}$ for the British Columbia coal dust. The flammability limit data at constant volume for a number of coal dusts including those tested in the present study are displayed in Table 17.

4. CONCLUSIONS

A series of tests has been carried out in the 180 litre cylindrical Hartmann-type dust explosion vessel to determine the lean flammability limits of dust-air mixtures at constant volume.

To establish the limit criterion and to assess the suitability of the apparatus and test procedure, a test dust was first used to compare the results with well-established data. The test dust was commerically available cornstarch with a mean particle size of $\sim 15\ \mu m$. The lean flammability limit at constant volume measured in the 180 litre vessel for cornstarch was found to be 75 gm/m^3 which is in very good agreement with earlier measurements in a 5 m^3 vessel. This confirms the suitability of the 180-litre explosion vessel for flammability limit studies.

Flammability limits for two coal dusts supplied to us under the auspisces of EMR were also measured in the 180 litre vessel. The Cape Breton coal sample (325 mesh, $< 44\ \mu m$) was found to have a lean flammability limit of 40 gm/m^3 which is identical to the previously measured flammability limit for Devco 26 coal dust (200 mesh, $< 74\ \mu m$). The British Columbia coal sample for which we have no particle size specification had a lean flammability limit of 150 gm/m^3.

5. REFERENCES

1. National Fire Protection Association, Fire Protection Handbook, 14th Edition, Section 3, NFPA, 1976.
2. Hartmann, I. Ind. Eng. Chem. 40, 752 (1948).
3. Dorsett, H.G., Jacobson, M., Nagy, J. and Williams, P.R. Laboratory Equipment and Test Procedures for Evaluating Explosibility of Dusts. Bureau of Mines Report of Investigations 5624, 1960.
4. Eggleston, L.A. and Pryor, A.J. Fire Technol. 3, 77 (1967).

5. Nagy, J. and Verakis, H.C. Development and Control of Dust Explosions, Marcel Dekker, New York, 1983.

6. Hertzberg, M., Cashdollar, K.L. and Opferman, J.J. "The Flammability of Coal-Dust-Air Mixtures". RI 8360, US Bureau of Mines, Pittsburgh, Pa., 1979.

7. Hertzberg, M., Cashdollar, K.L. and Lazzane, C.P. "The Limits of Flammability of Pulverized Coals and Other Dusts". Proc. of the 18th Symp. (International) on Combustion, The Combustion Institute, Pittsburgh, Pa., 1981, pp. 717-729.

8. Cashdollar, K.L., Hertzberg, M. and Richmond, J.K. "Inhibition of Coal Dust Explosions: Comparison of the 8-Liter Laboratory Chamber and Experimental Mine". Proc. of the 20th International Conference of Safety in Mines Research Institutes, Sheffield, England, Oct. 3-7, 1983.

9. Cashdollar, K.L. and Hertzberg, M. "20-L Explosibility Test Chamber for Dusts and Gases". Rev. Sci. Inst. 56, 1985, pp. 596-602.

10. Cashdollar, K.L., Hertzberg, M. and Conti, R.S. "Explosion Hazards of Oil Shale Dusts: Limits, Pressures, and Ignitability". Proc. of the 17th Oil Shale Symposium, Colorado School of Mines Press, Golden, Co. 1984, pp. 243-254.

11. Hertzberg, M., Cashdollar, K.L., Zlochower, I. and Ng, D.L. "Inhibition and Extinction of Explosions in Heterogeneous Mixtures". Proc.

of the 20th Symp. (International) on Combustion, The Combustion Institute, Pittsburgh, Pa., 1985, pp. 1691-1700.

12. Bartknecht, W. "Preventive and Design Measures for Protection Against Dust Explosions" in Industrial Dust Explosions, Ed. Cashdollar and Hertzberg, ASTM STP 958, 1987, pp. 158-190.

13. Cashdollar, K.L., Sapko, M.J., Weiss, E.S. and Hertzberg, M. "Laboratory and Mine Dust Explosion Research at the Bureau of Mines" in Industrial Dust Explosions, Ed. Cashdollar and Hertzberg, ASTM STP 958, 1987, pp. 107-123.

14. Gaug, M., Knystautas, R., Lee, J.H., Benedick, W.B., Nelson, L. and Shepherd, J. "The Lean Flammability Limits of Hybrid Mixtures". Progress in Astronautics and Aeronautics, Vol. 105, Dynamics of Reactive Systems, AIAA, 1986, pp. 155- 168.

15. Coward, H.F. and Jones, G.W. "Limits of Flammability of Gases and Vapors". Bulletin 503, US Bureau of Mines, Pittsburgh, 1952.

16. Hertzberg, M. "The Flammability Limits of Gases, Vapors and Dusts: Theory and Experiment". Proc. International Conference on Fuel-Air Explosions, McGill University, Montreal, Canada. Univ. of Waterloo Press, SM-16, 1982, pp. 3-48.

17. Bond, J.F., Knystautas, R. and Lee, J.H.S. "Influence of Turbulence on Dust and Gas Explosions in Closed Vessels". Progress in Astro-

nautics and Aeronautics, Vol. 106, Dynamics of Explosions, AIAA, 1986, pp. 571-584.

18. Jarosinski, J., Lee, J.H., Knystautas, R. and Crowley, J.D. "Quenching of Dust-Air Flamesss". Proc. of the 21st Symp. (International) on Combustion, The Combustion Institute, Pittsburgh, Pa., 1988, pp. 1917-1924.

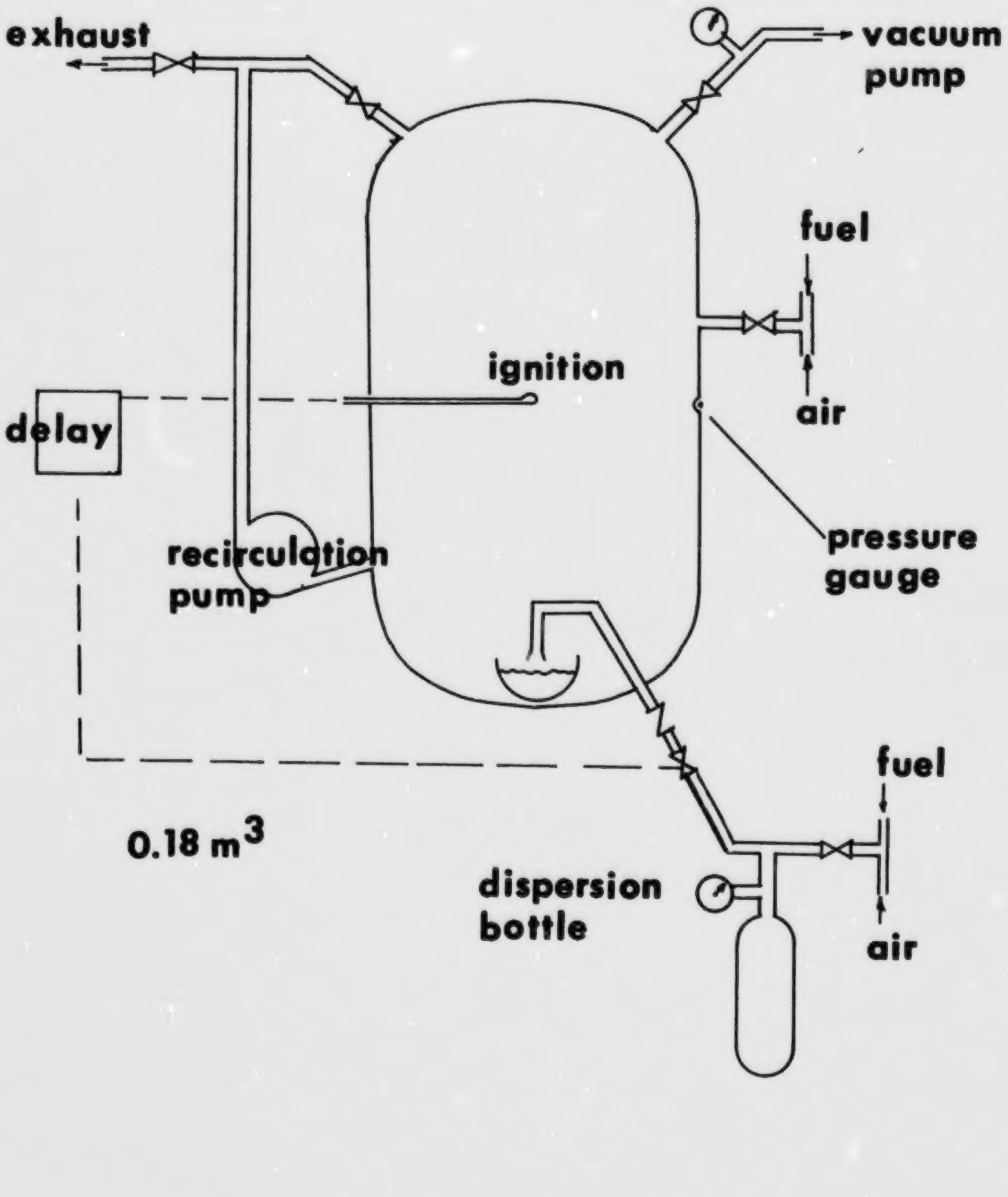
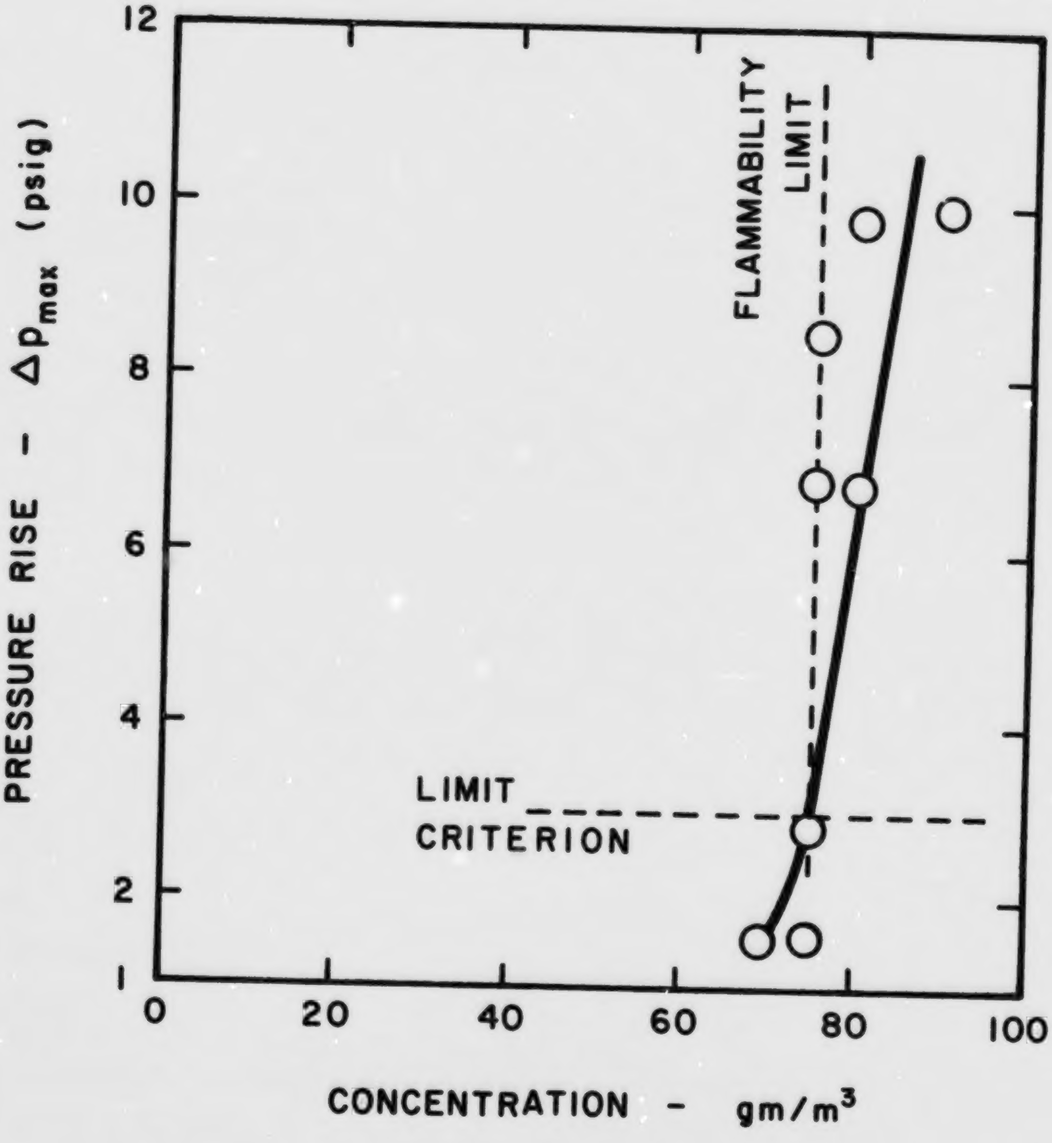

exhaust
vacuum pump
fuel
air
ignition
delay
recirculation pump
pressure gauge
fuel
0.18 m^3
dispersion bottle
air

FIG · 1



CORNSTARCH

200 MSEC DELAY TO IGNITION

FIG. 2

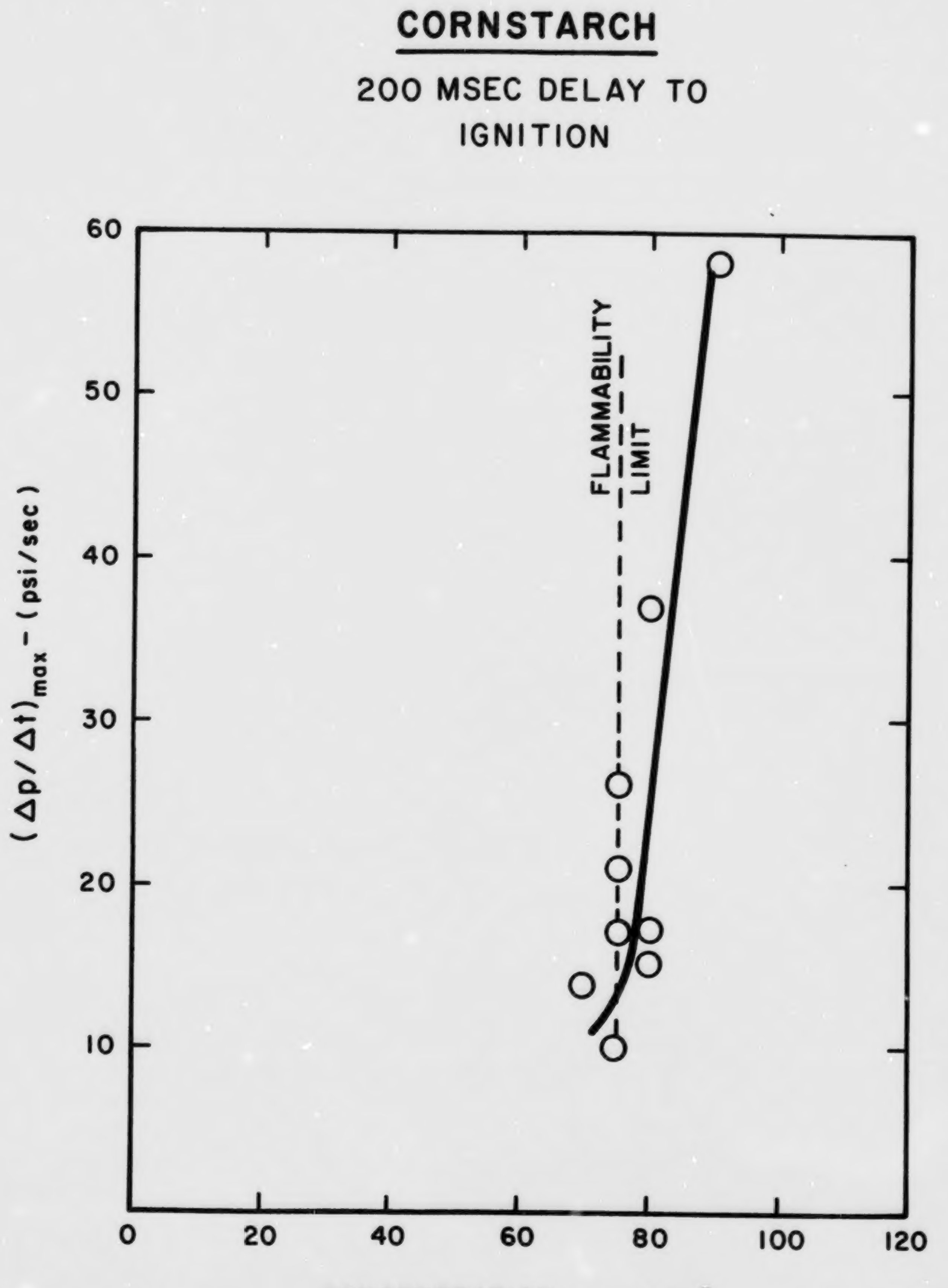

CORNSTARCH
200 MSEC DELAY TO IGNITION
FLAMMABILITY LIMIT
$(\Delta p/\Delta t)_{max}$ - (psi/sec)
60
50
40
30
20
10
0
20
40
60
80
100
120
CONCENTRATION - gm/m^3

FIG · 3

CAPE BRETON COAL DUST

200 MSEC DELAY TO IGNITION

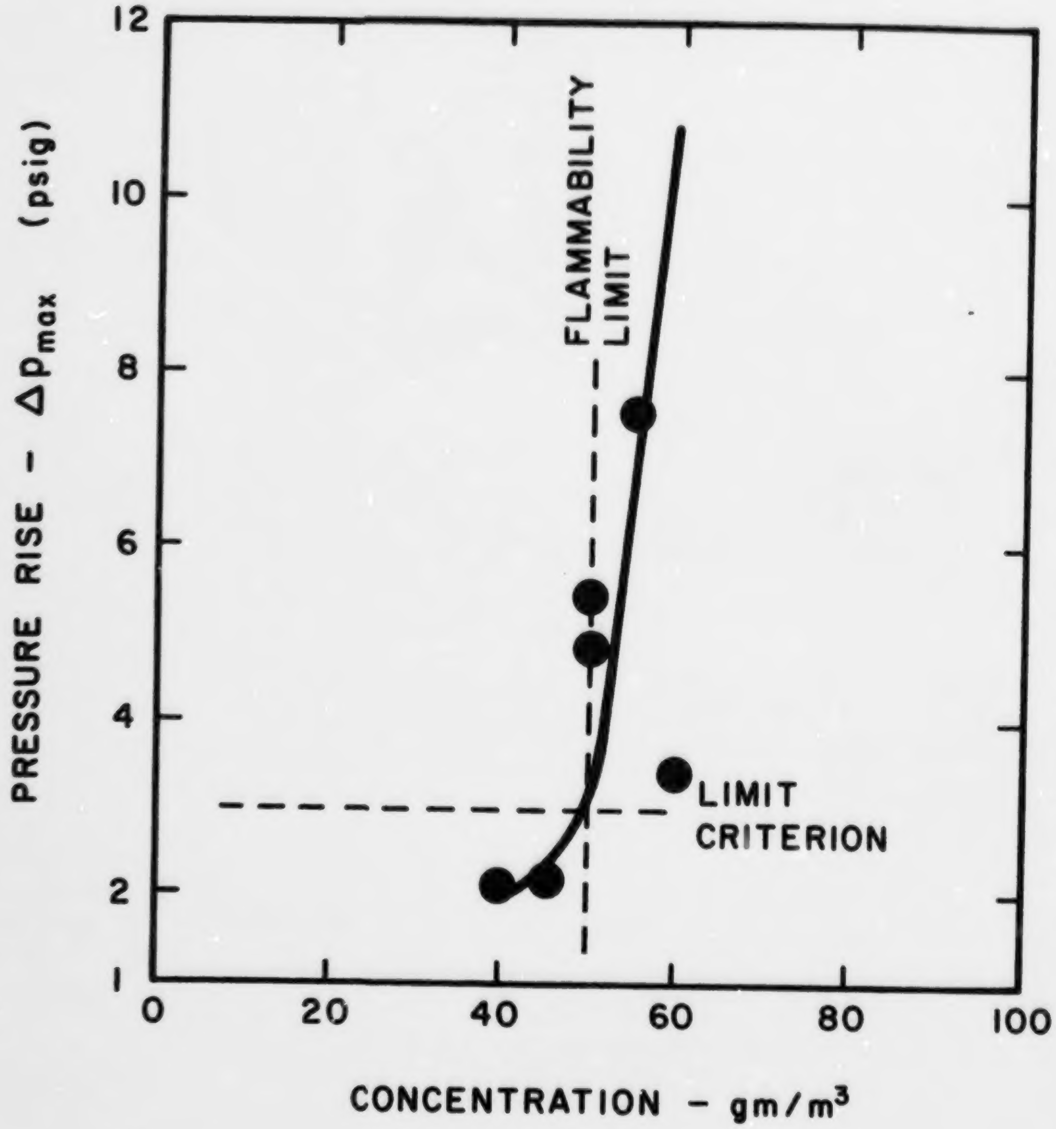
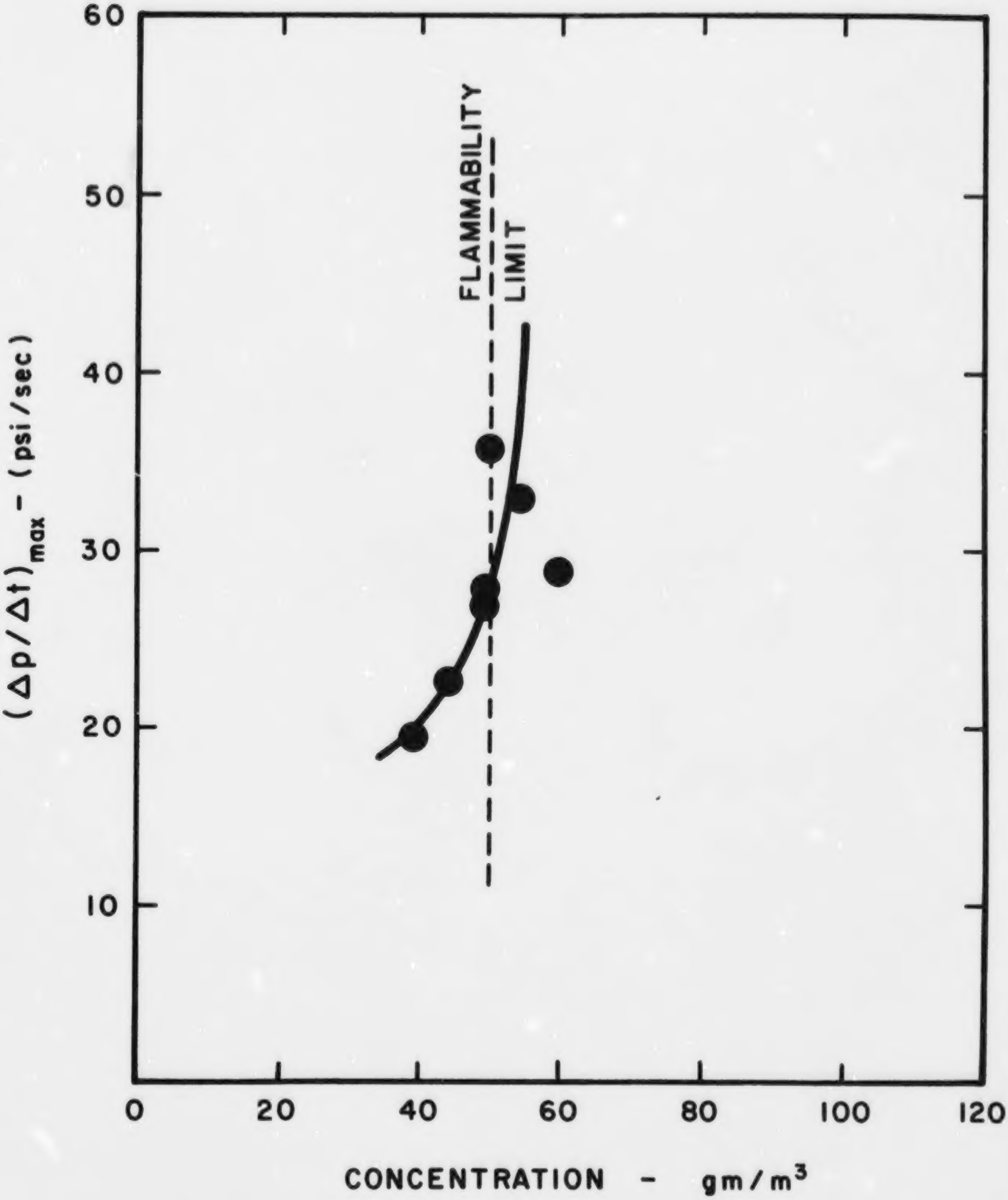


FIG. 4

CAPE BRETON COAL DUST

200 MSEC DELAY TO IGNITION



FIG·5

BRITISH COLUMBIA COAL DUST

100 MSEC DELAY TO IGNITION

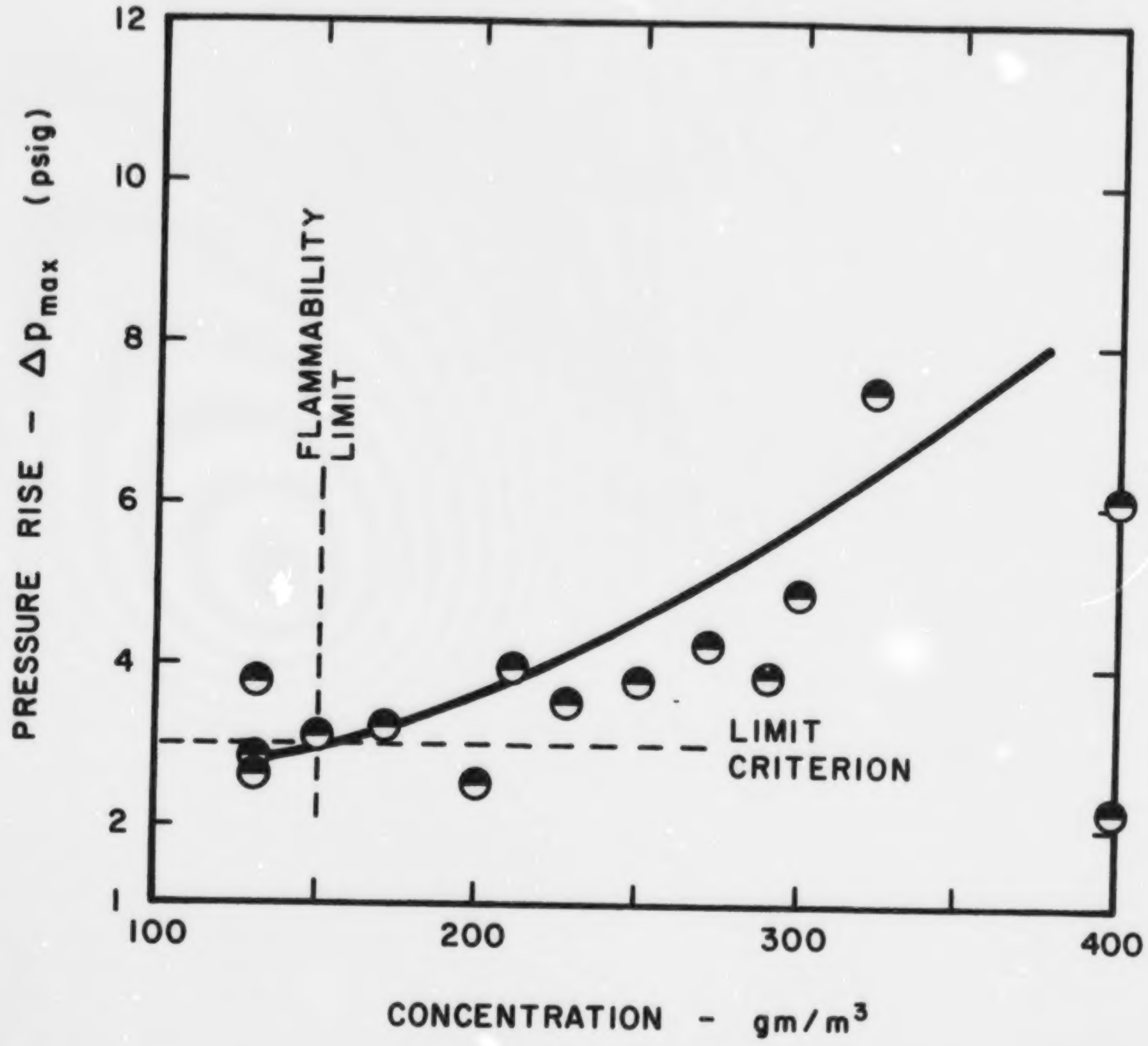
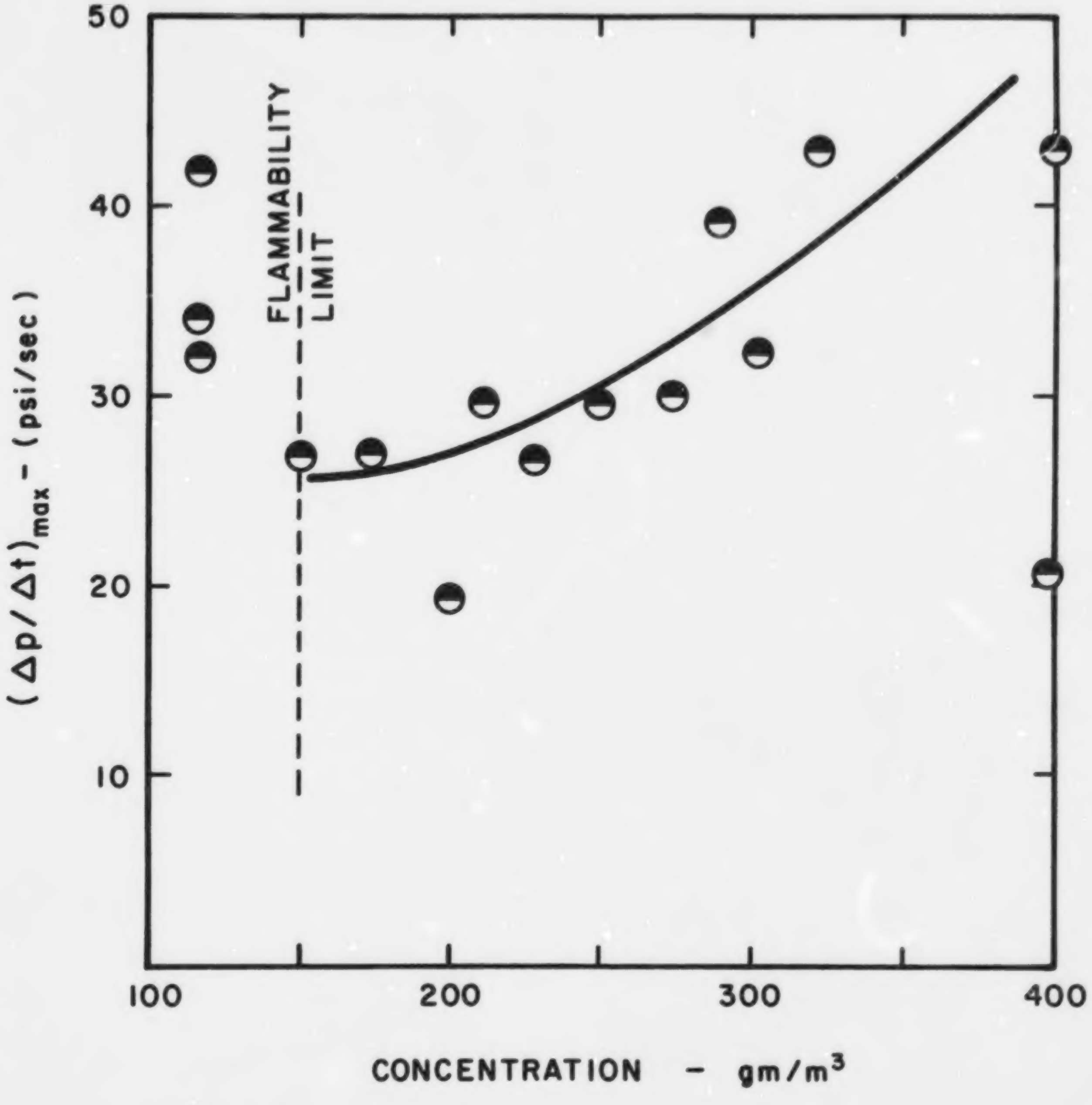


FIG - 6

BRITISH COLUMBIA COAL DUST

100 MSEC DELAY TO IGNITION



FIG·7

Table # 1
Coal Dust
Mesh. 325 - C. Breton
Time delay : 100 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
30	0.1	10	1.754	19.493
30	0.1	10	2.729	38.986
40	0.1	10	3.509	31.189
40	0.1	10	3.119	50.682
50	0.1	10	7.602	51.982

Table # 2
Coal Dust
Mesh. 325 - C. Breton
Time delay : 200 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
40	0.1	10	2.144	19.943
45	0.1	10	2.144	22.742
50	0.1	10	4.483	27.857
50	0.1	10	5.458	35.088
55	0.1	10	7.602	33.138
60	0.1	10	3.119	29.240

Table # 3
Coal Dust
Mesh. 325 - C. Breton
Time delay : 300 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
50	0.1	10	2.339	17.721
50	0.1	10	2.729	24.366
60	0.1	10	3.509	34.113
60	0.1	10	2.339	22.278
60	0.1	10	3.509	35.093

Table # 4
Coal Dust
Mesh. 325 - C. Breton
Time delay : 400 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
55	0.2	10	2.729	16.244
60	0.2	10	3.119	17.057
70	0.2	10	4.373	20.576
120	0.2	10	11.696	41.423

Table # 5
Coal Dust
Mesh. 325 - C. Breton
Time delay : 500 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
50	0.2	10	2.144	14.62
60	0.2	10	2.534	11.371
70	0.2	10	3.119	24.366
70	0.2	10	2.144	11.371
70	0.2	10	3.119	12.995

Table # 6
Coal Dust
Mesh. 325 - C. Breton
Time delay : 600 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
70	0.2	10	2.339	27.847
70	0.2	10	2.924	27.847
80	0.2	10	2.729	38.986
90	0.2	10	3.119	43.318
90	0.2	10	2.339	27.487
90	0.2	10	2.729	32.489

Table # 7
Coal Dust
20 Kg B.C.
Time delay : 100 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
130	0.1	10	2.729	32.105
130	0.1	10	3.899	34.113
130	0.1	10	2.534	42.233
150	0.1	10	3.119	27.847
170	0.1	10	3.142	27.847
200	0.1	10	2.534	19.493
210	0.1	10	3.899	29.240
230	0.1	10	3.509	27.847
250	0.1	10	3.704	29.989
270	0.1	10	4.094	29.989
280	0.1	10	3.889	38.986
300	0.1	10	4.288	32.489
320	0.1	10	7.602	43.318
400	0.1	10	2.144	21.440
400	0.1	10	6.043	43.318

Table # 8
Coal Dust <1>
20 Kg B.C. (heated for 1 Hr.)
Time delay : 200 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
55	0.1	10	1.754	12.995
80	0.1	10	1.754	13.760
90	0.1	10	1.949	13.760
100	0.1	10	1.949	14.995
100	0.1	10	2.729	16.244
100	0.1	10	1.559	13.112
120	0.1	10	2.144	19.493
120	0.1	10	2.144	17.327
150	0.1	10	1.949	12.995
250	0.1	10	0.974	9.747

Table # 9
Coal Dust <2>
20 Kg B.C. (heated for 24 Hr.)
Time delay : 200 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
150	0.1	10	2.534	23.787
170	0.1	10	2.729	21.450
200	0.1	10	2.729	16.088
200	0.1	10	2.534	19.812
230	0.1	10	2.144	19.305
250	0.1	10	2.144	22.278
260	0.1	10	2.340	18.347
260	0.1	10	3.899	22.711
280	0.1	10	2.729	16.244
300	0.1	10	2.339	9.747
300	0.1	10	2.144	16.708
300	0.1	10	3.899	24.131
350	0.1	10	2.339	18.347
350	0.1	10	3.185	19.493
500	0.1	10	2.339	12.183

Table # 10
Cornstarch

Time delay : 200 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
70	0.1	10	1.559	13.924
75	0.1	10	2.729	25.990
75	0.1	10	6.823	21.118
75	0.1	10	8.576	15.316
75	0.1	10	1.559	10.633
80	0.1	10	6.823	14.620
80	0.1	10	9.746	37.362
80	0.1	10	1.949	17.057
90	0.1	10	9.746	58.480

Table # 11
Cornstarch

Time delay : 300 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
70	0.1	10	2.339	21.659
75	0.1	10	2.339	16.244
80	0.1	10	2.830	19.493
80	0.1	10	7.790	32.489
80	0.1	10	2.720	25.991
80	0.1	10	5.458	16.244
80	0.1	10	2.339	19.490
85	0.1	10	3.700	22.933
90	0.1	10	3.509	21.659
90	0.1	10	1.754	11.700
90	0.1	10	2.339	22.280
90	0.1	10	2.924	17.540
95	0.1	10	6.823	35.740
100	0.1	10	6.823	48.730

Table # 12
Cornstarch

Time delay : 400 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
60	0.2	10	1.949	27.487
65	0.2	10	1.949	19.493
70	0.1	10	5.848	16.244
70	0.2	10	2.729	38.986
80	0.1	10	3.216	19.493
80	0.1	10	1.949	19.943
90	0.1	10	2.339	13.924
95	0.2	10	3.119	38.986
100	0.1	10	5.848	21.659

Table # 13
Cornstarch

Time delay : 500 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
80	0.2	10	3.958	43.318
80	0.2	10	2.729	48.733
80	0.2	10	1.949	24.366
85	0.2	10	3.704	43.318
85	0.2	10	2.339	24.366
90	0.2	10	3.899	32.489
90	0.2	10	3.119	27.847
95	0.2	10	7.212	38.986

Table #14
Cornstarch

Time delay : 600 miliseconds

concentration (g/m3)	time scale (sec/div)	pressure scale (psi/div)	(dP)comb. (psi)	(dP/dt)max (psi/sec)
80	0.2	10	2.144	14.620
90	0.2	10	1.949	14.620
95	0.2	10	8.187	14.620
95	0.2	10	2.534	10.965
100	0.2	10	5.848	16.244

FLAMMABILITY LIMIT CONCENTRATION - *GM/M³*

DELAY TO IGNITION (MSEC)	*CORNSTARCH*	*CAPE BRETON COAL DUST*	*BRITISH COLUMBIA COAL DUST*
100	75	40	150
200	75	50	-
300	85	60	-
400	95	60	-
500	85	70	-
600	100	90	-

TABLE 15

FLAMMABILITY LIMITS IN CORNSTARCH-AIR MIXTURES FOR CONSTANT VOLUME COMBUSTION

JACOBSON ET AL.	1.2 L	40 GM/M^3
GAUG ET AL.	5 M^3	70 GM/M^3
McGILL UNIV.	180 L	75 – 80 GM/M^3

TABLE 16

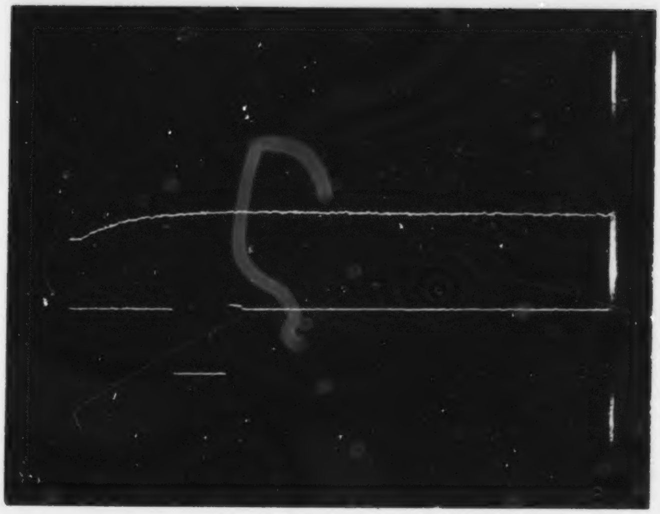
FLAMMABILITY LIMITS IN COAL DUST-AIR MIXTURES FOR CONSTANT VOLUME COMBUSTION

GILSONITE	(22-26 μM)	7.8L HERTZBERG ET AL.	65 GM/M^3
PITTSBURGH	(7-9 μM)	7.8L HERTZBERG ET AL.	130 GM/M^3
POCAHONTAS	(20-40 μM)	7.8L HERTZBERG ET AL.	230 GM/M^3
READING	(3-5 μM)	7.8L HERTZBERG ET AL.	450 GM/M^3
DEVCO 26	(70 μM)	1.2L FENG	67 GM/M^3
DEVCO 26	(70 μM)	180L McGILL UNIV.	40 GM/M^3
CAPE BRETON	(44 μM)	180L McGILL UNIV.	40 GM/M^3
BRITISH COLUMBIA	(UNKNOWN)	180L McGILL UNIV.	150 GM/M^3

TABLE 17

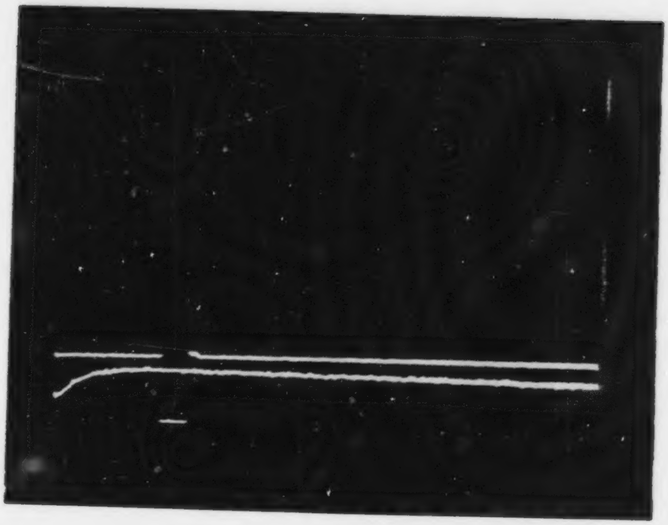
Igniter only
Time Delay : 200 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
  (sec/div)
-Pressure Scale: 10
  (psi/div)
-(dp) : 0.8
  (psi)

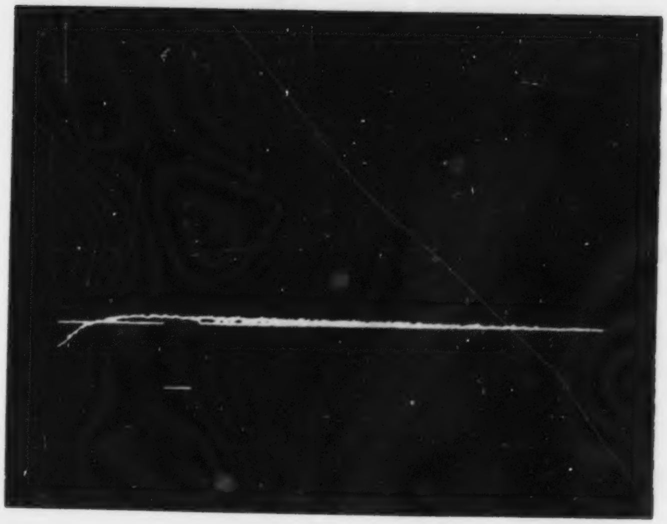


Igniter only
Time Delay : 400 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-(dp) : 0.0
(psi)

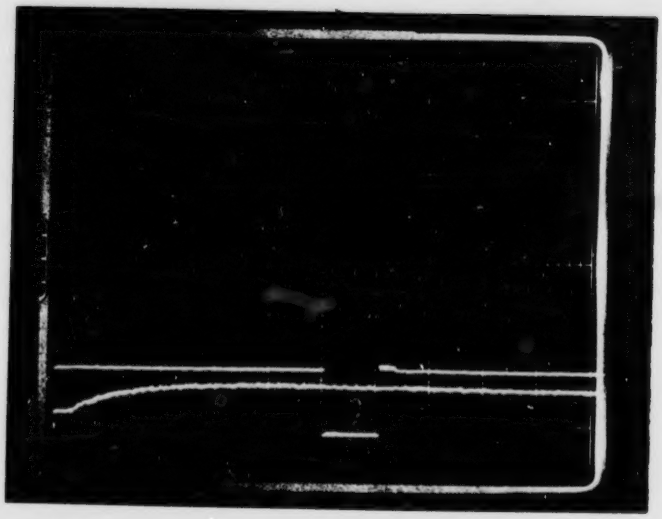


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-(dp) : 0.0
(psi)

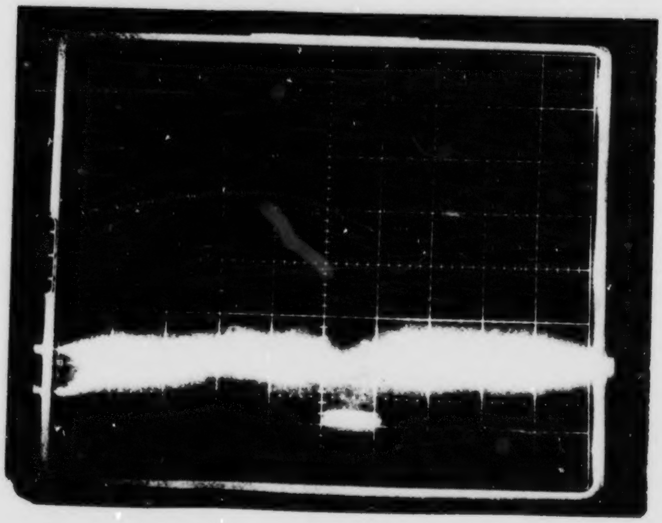


Igniter only
Time Delay : 500 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-(dp) : 0.6
(psi)

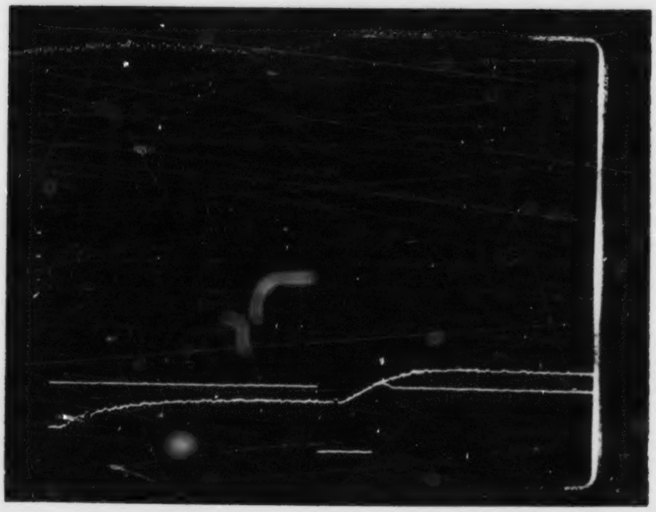


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-(dp) : 0.5
(psi)



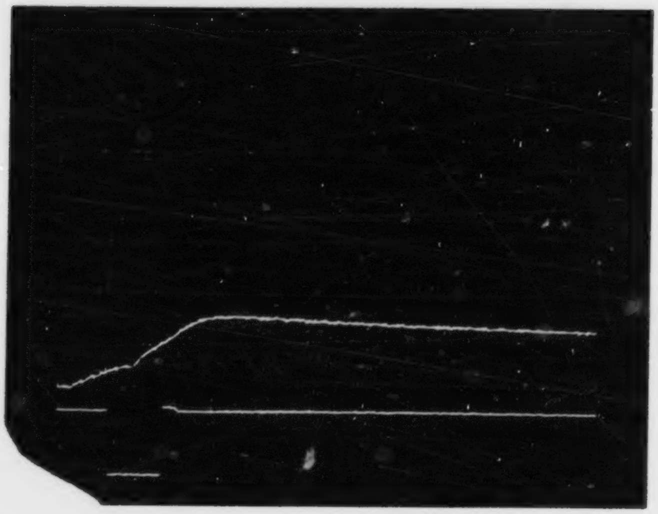
Igniter only
Time Delay : 500 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-(dp) : ~~0.5~~ 2.0
(psi)

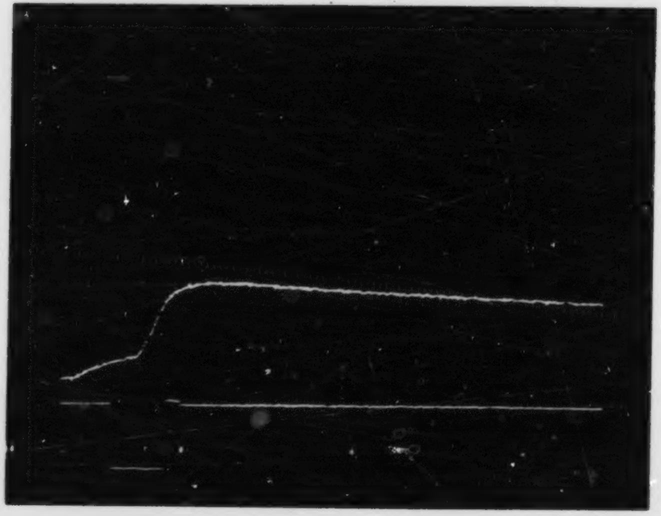


Coal Dust (C.Breton)
Time Delay : 100 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Press.Scale: 10
 (psi/div)
-Concentration: 30
 (g/m3)
-(dp)comb : 1.754
 (psi)
-(dp/dt)max : 19.493
 (psi/div)

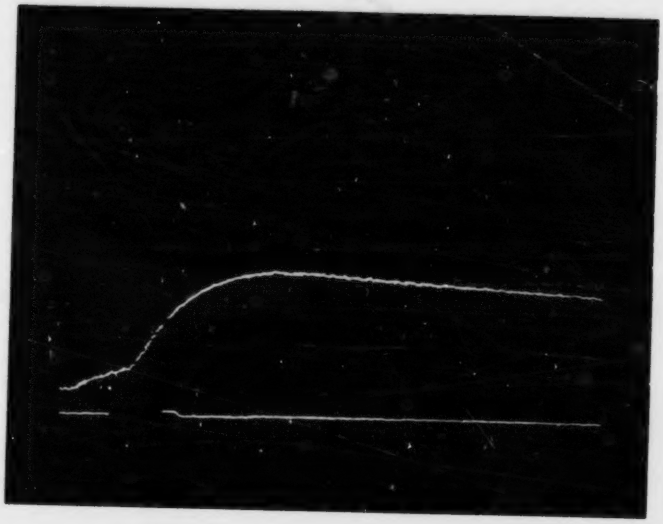


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 30
 (g/m3)
-(dp)comb : 2.729
 (psi)
-(dp/dt)max : 38.986
 (psi/sec)

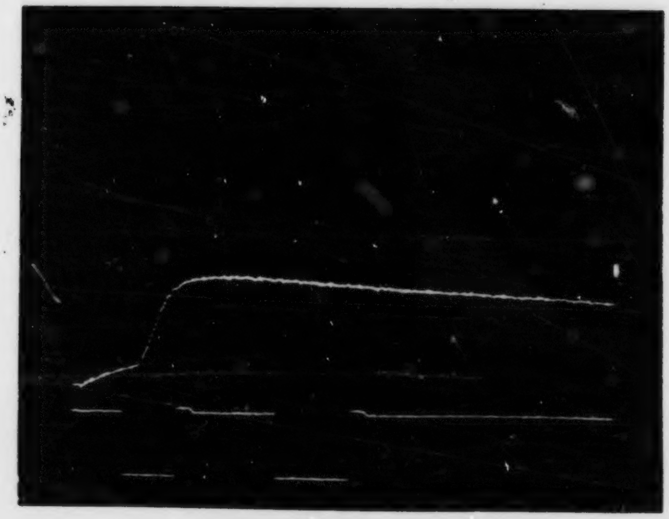


Coal Dust (C.Breton)
Time Delay : 100 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 40
 (g/m3)
-(dp)comb : 3.509
 (psi)
-(dp/dt)max : 31.189
 (psi/sec)

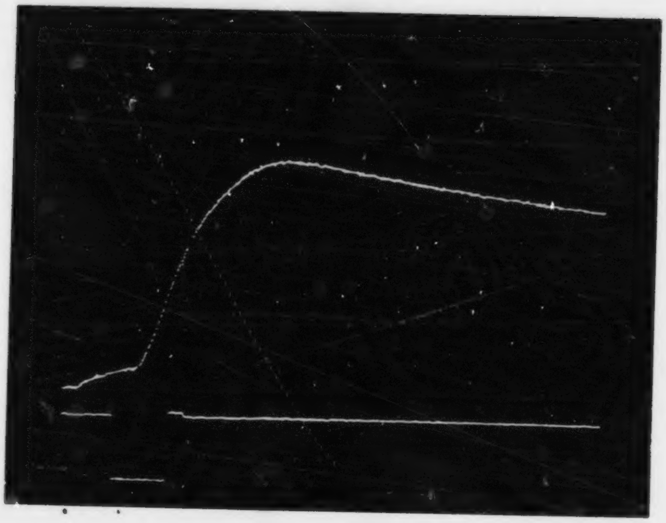


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 40
 (g/m3)
-(dp)comb : 3.119
 (psi)
-(dp/dt)max : 50.682
 (psi/sec)



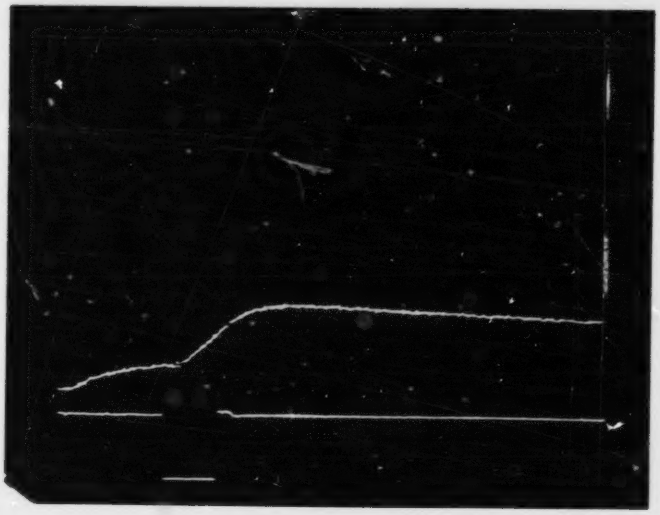
Coal Dust (C.Breton)
Time Delay : 100 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 50
 (g/m3)
-(dp)comb : 7.602
 (psi)
-(dp/dt)max : 51.982
 (psi/sec)

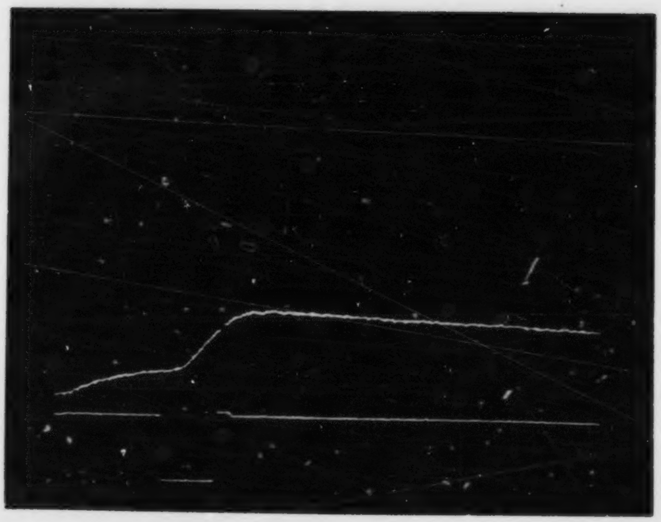


Coal Dust (C.Breton)
Time Delay : 200 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 40
 (g/m3)
-(dp)comb : 2.144
 (psi)
-(dp/dt)max : 19.943
 (psi/sec)

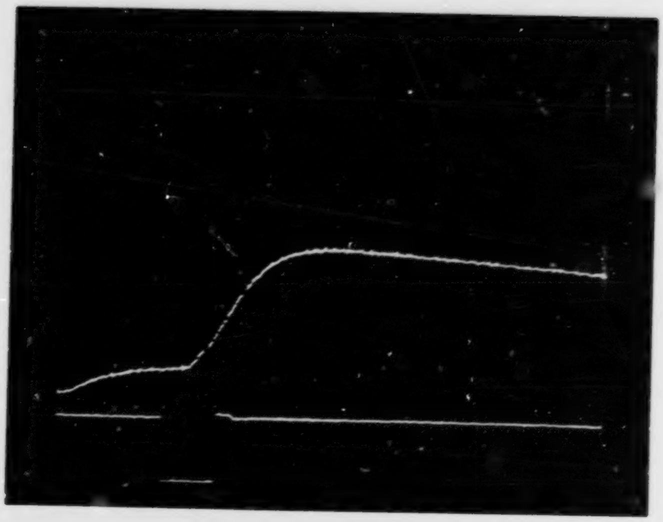


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 45
 (g/m3)
-(dp)comb : 2.144
 (psi)
-(dp/dt)max : 22.742
 (psi/sec)

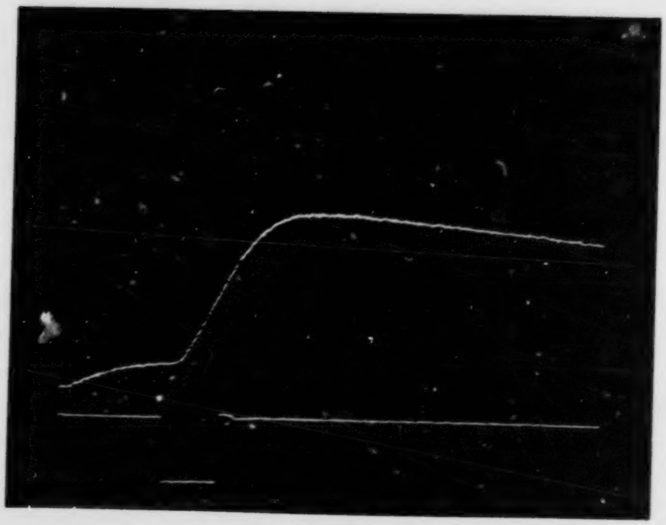


Coal Dust (C.Breton)
Time Delay : 200 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 50
(g/m3)
-(dp)comb : 4.483
(psi)
-(dp/dt)max : 27.857
(psi/sec)

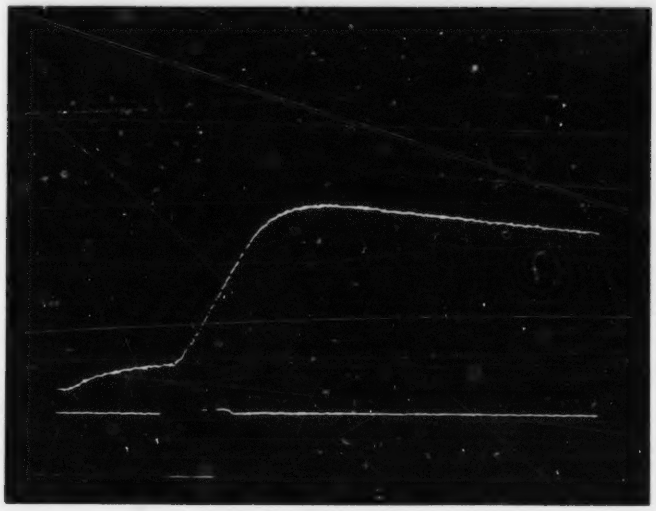


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 50
(g/m3)
-(dp)comb : 5.458
(psi)
-(dp/dt)max : 35.088
(psi/sec)

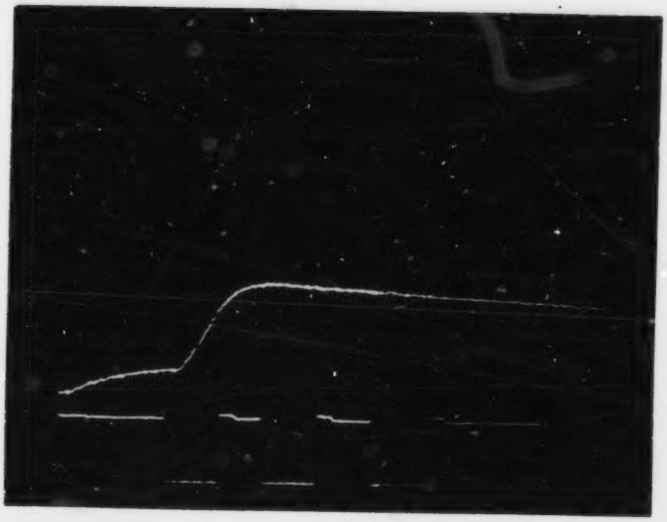


Coal Dust (C.Breton)
Time Delay : 200 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 55
 (g/m3)
-(dp)comb : 7.602
 (psi)
-(dp/dt)max : 33.138
 (psi/sec)

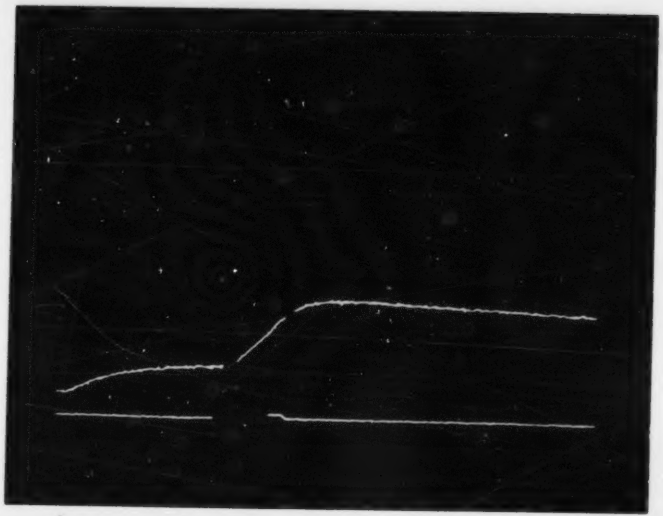


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 60
 (g/m3)
-(dp)comb : 3.119
 (psi)
-(dp/dt)max : 29.240
 (psi/sec)

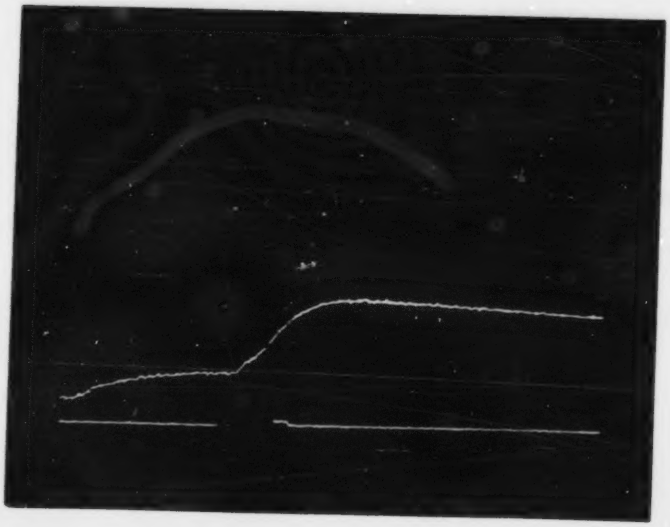


Coal Dust (C.Breton)
Time Delay : 300 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 50
(g/m3)
-(dp)comb : 2.339
(psi)
-(dp/dt)max : 17.721
(psi/sec)

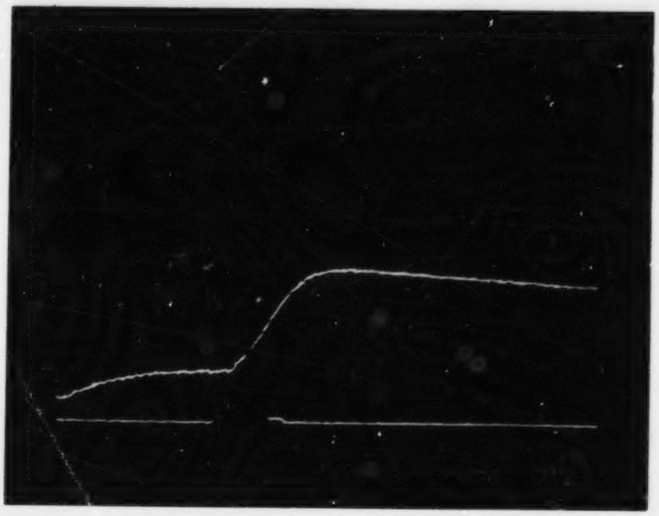


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 50
(g/m3)
-(dp)comb : 2.729
(psi)
-(dp/dt)max : 24.366
(psi/sec)

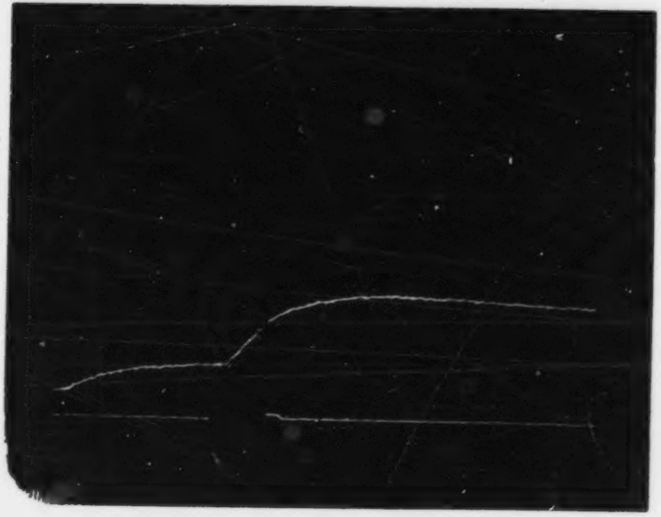


Coal Dust (C.Breton)
Time Delay : 300 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 60
 (g/m3)
-(dp)comb : 3.509
 (psi)
-(dp/dt)max : 34.113
 (psi/sec)

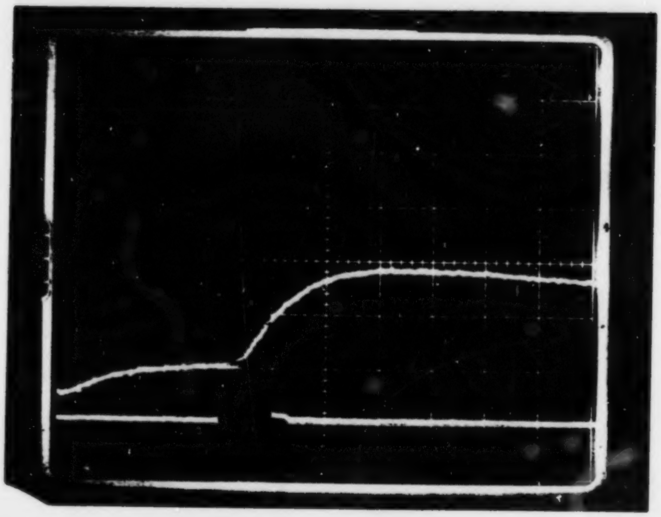


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 60
 (g/m3)
-(dp)comb : 2.339
 (psi)
-(dp/dt)max : 22.278
 (psi/sec)



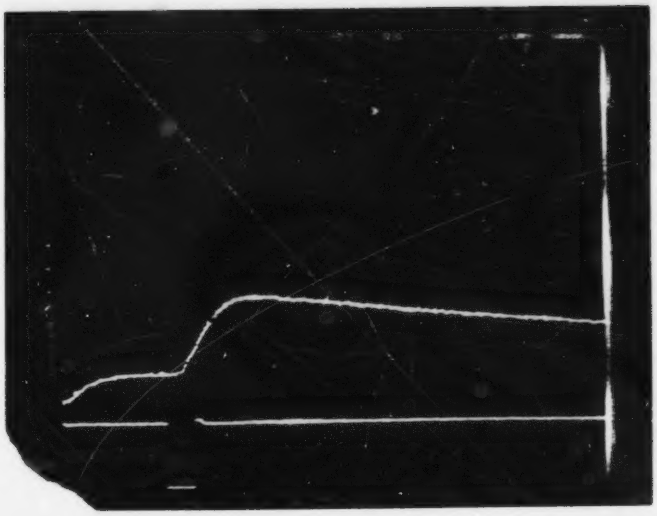
Coal Dust (C.Breton)
Time Delay : 300 miliseconds

-Dispersion Pressure : 200 psig
-Electric Match 1.2g Black Powder
-Po : 1 atm
-Time Scale: 0.1 (sec/div)
-Pressure Scale: 10 (psi/div)
-Concentration: 60 (g/m3)
-(dp)comb : 3.509 (psi)
-(dp/dt)max : 35.093 (psi/sec)

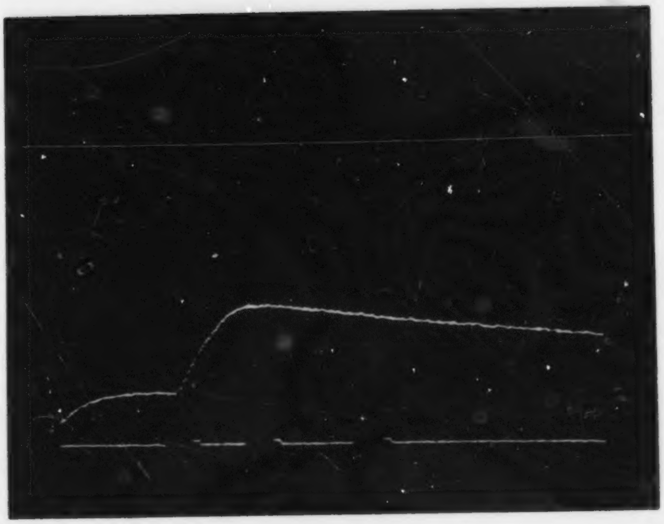


Coal Dust (C.Breton)
Time Delay : 400 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 55
 (g/m3)
-(dp)comb : 2.729
 (psi)
-(dp/dt)max : 16.244
 (psi/sec)

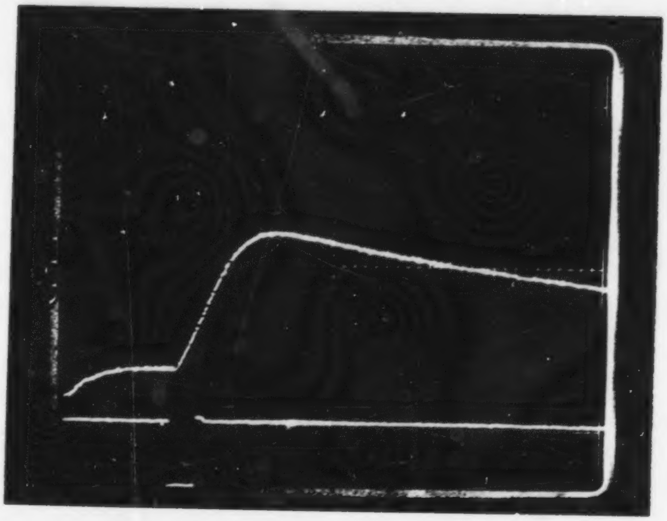


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 60
 (g/m3)
-(dp)comb : 3.119
 (psi)
-(dp/dt)max : 17.057
 (psi/sec)

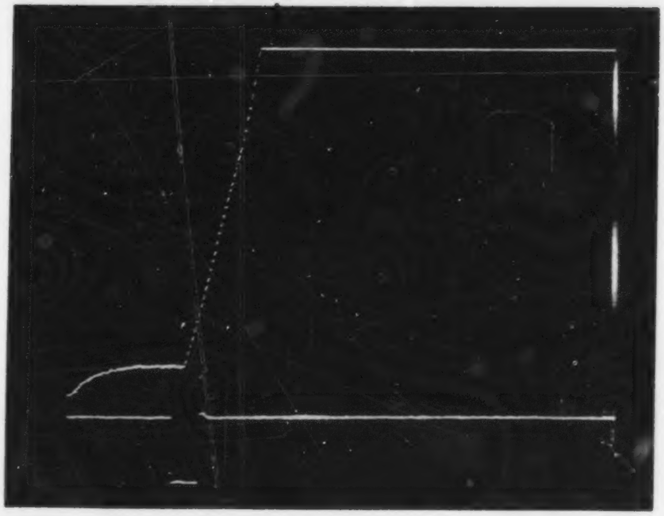


Coal Dust (C.Breton)
Time Delay : 400 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 70
(g/m3)
-(dp)comb : 4.373
(psi)
-(dp/dt)max : 20.576
(psi/sec)



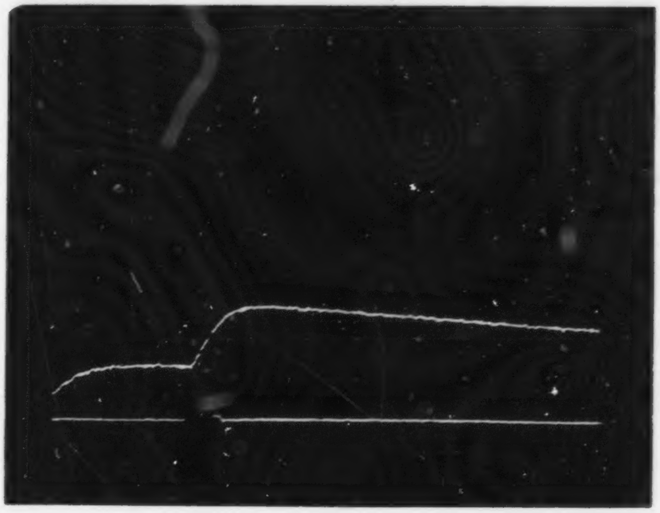
-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 120
(g/m3)
-(dp)comb : 11.696
(psi)
-(dp/dt)max : 41.423
(psi/sec)



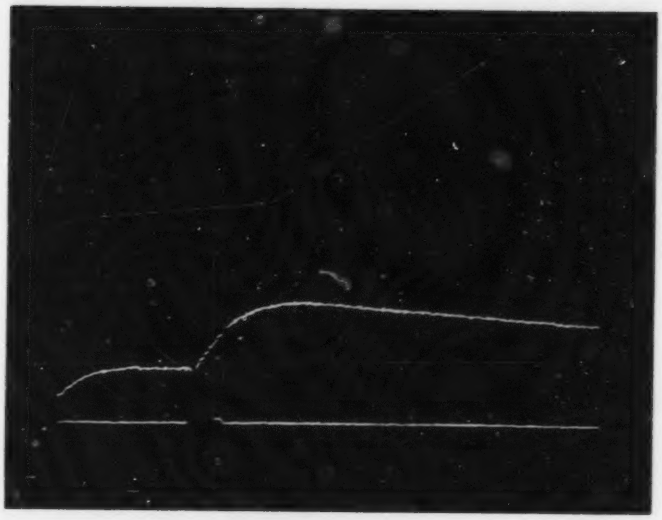
X

Coal Dust (C.Breton)
Time Delay : 500 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 50
 (g/m3)
-(dp)comb : 2.144
 (psi)
-(dp/dt)max : 14.620
 (psi/sec)

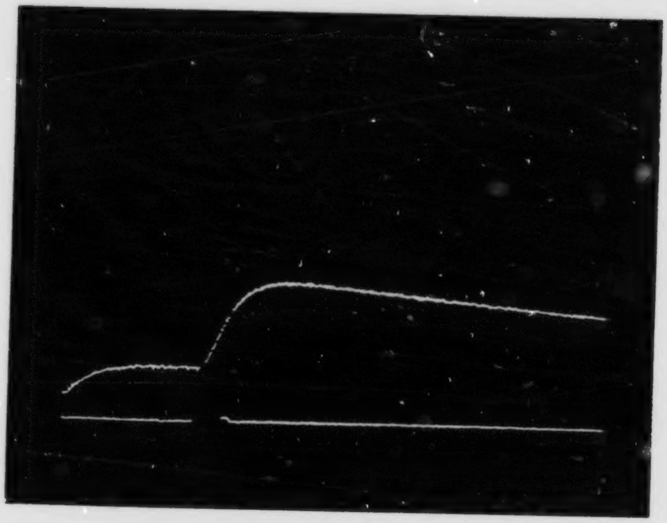


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 60
 (g/m3)
-(dp)comb : 2.534
 (psi)
-(dp/dt)max : 11.371
 (psi/sec)

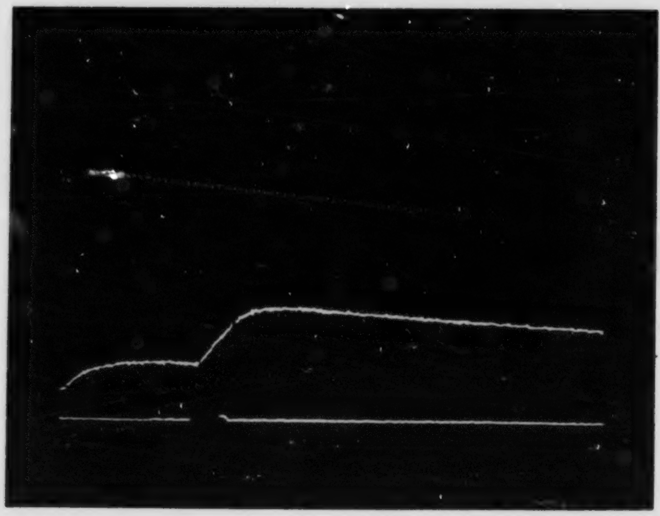


Coal Dust (C.Breton)
Time Delay : 500 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 70
 (g/m3)
-(dp)comb : 3.119
 (psi)
-(dp/dt)max : 24.366
 (psi/sec)

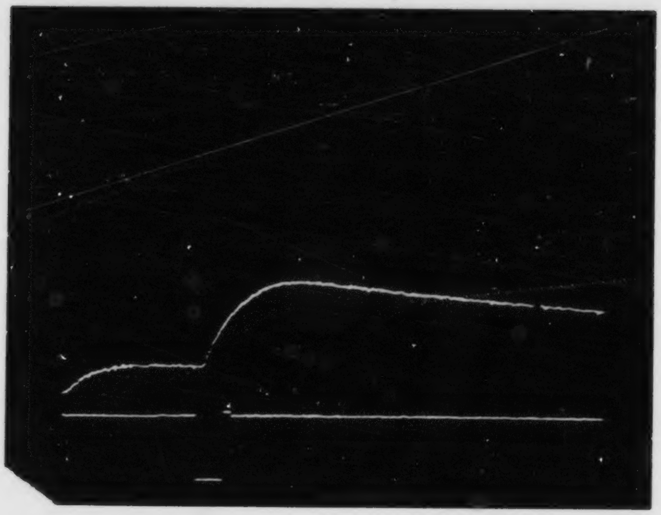


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 70
 (g/m3)
-(dp)comb : 2.144
 (psi)
-(dp/dt)max : 11.371
 (psi/sec)



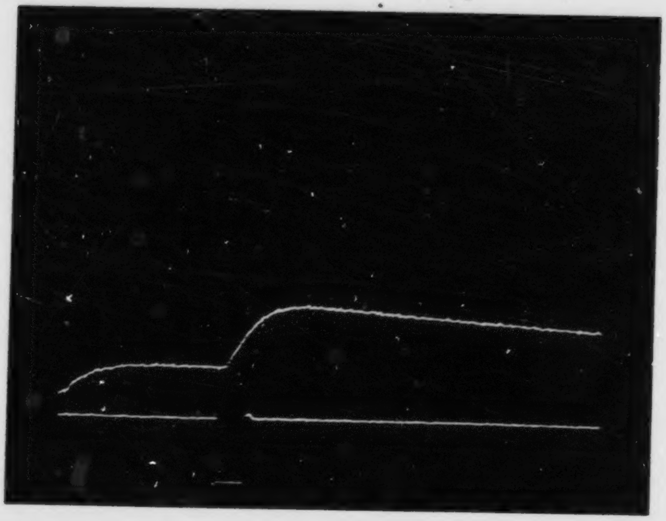
Coal Dust (C.Breton)
Time Delay : 500 miliseconds

- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.2 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 70 (g/m3)
- -(dp)comb : 3.119 (psi)
- -(dp/dt)max : 12.995 (psi/sec)

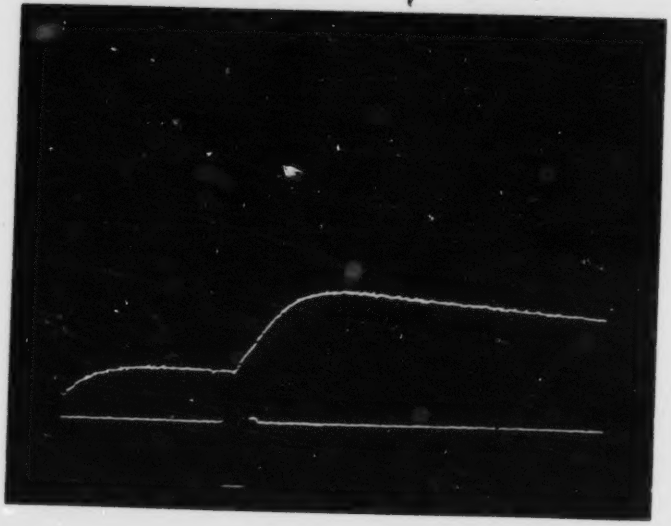


Coal Dust (C.Breton)
Time Delay : 600 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale:10
(psi/div)
-Concentration: 70
(g/m3)
-(dp)comb : 2.339
(psi)
-(dp/dt)max : 27.847
(psi/sec)

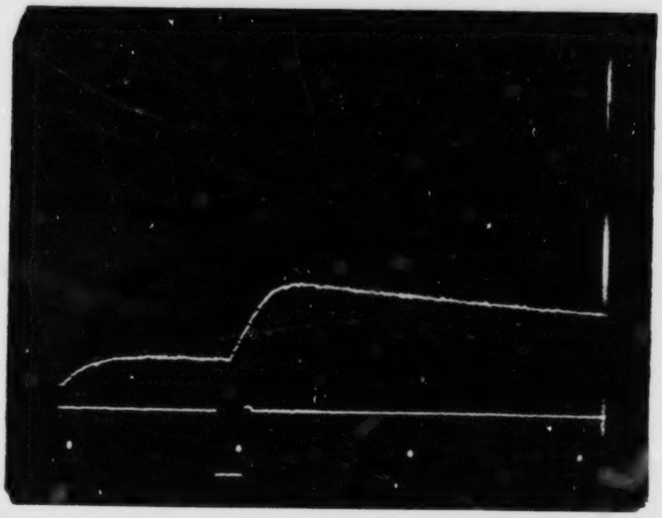


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 70
(g/m3)
-(dp)comb : 2.924
(psi)
-(dp/dt)max : 27.847
(psi/sec)

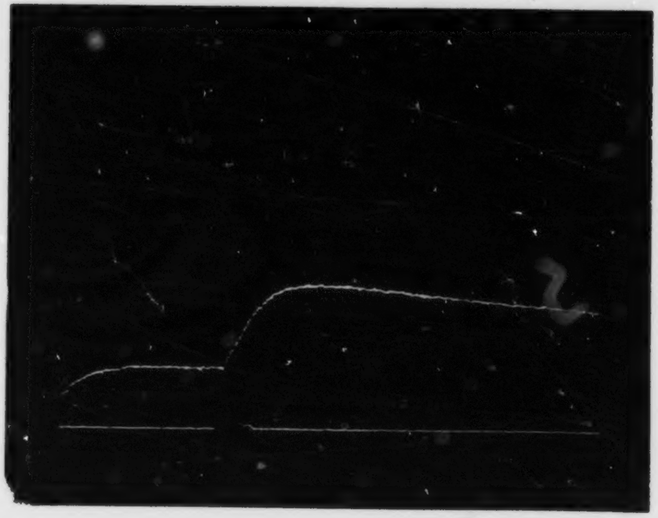


Coal Dust (C.Breton)
Time Delay : 600 miliseconds

- -Dispersion
 Pressure : 200 psig
- -Electric Match 1.2g
 Black Powder
- -Po : 1 atm
- -Time Scale: 0.2
 (sec/div)
- -Pressure Scale: 10
 (psi/div)
- -Concentration: 80
 (g/m3)
- -(dp)comb : 2.729
 (psi)
- -(dp/dt)max : 38.986
 (psi/sec)

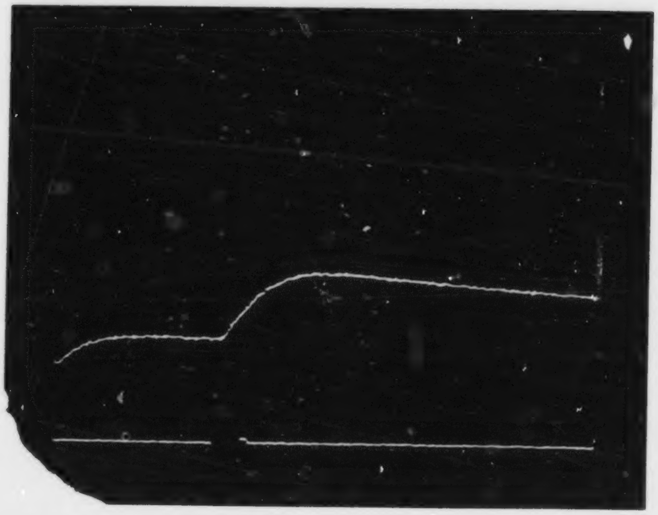


- -Dispersion
 Pressure : 200 psig
- -Electric Match 1.2g
 Black Powder
- -Po : 1 atm
- -Time Scale: 0.2
 (sec/div)
- -Pressure Scale: 10
 (psi/div)
- -Concentration: 90
 (g/m3)
- -(dp)comb : 3.119
 (psi)
- -(dp/dt)max : 43.318
 (psi/sec)

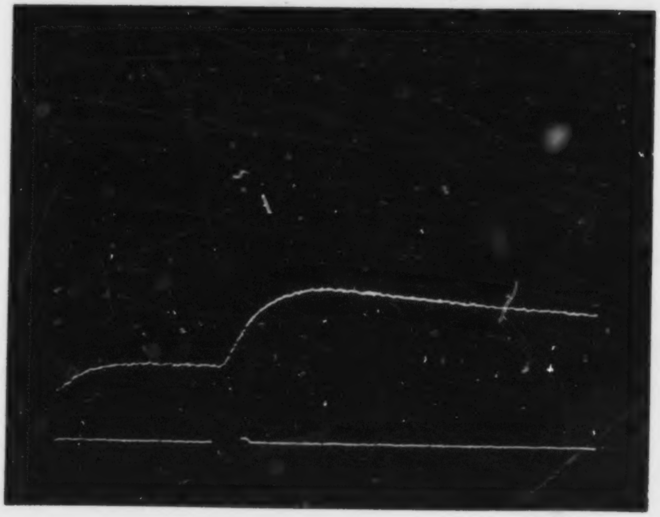


Coal Dust (C.Breton)
Time Delay : 600 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 90
(g/m3)
-(dp)comb : 2.339
(psi)
-(dp/dt)max : 27.847
(psi/sec)

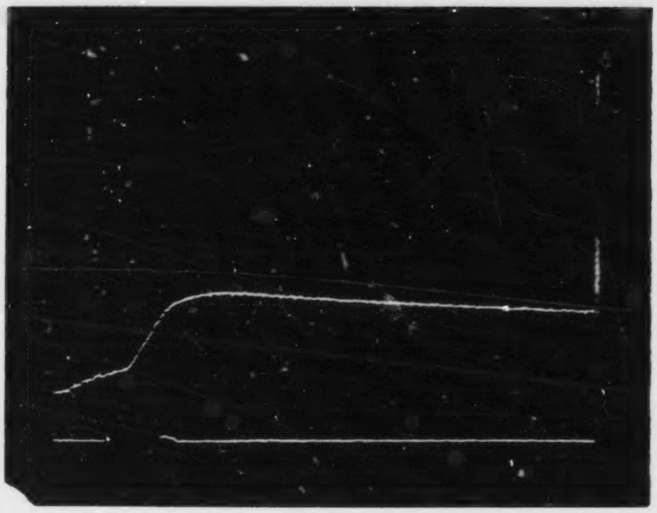


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 90
(g/m3)
-(dp)comb : 2.729
(psi)
-(dp/dt)max : 32.489
(psi/sec)

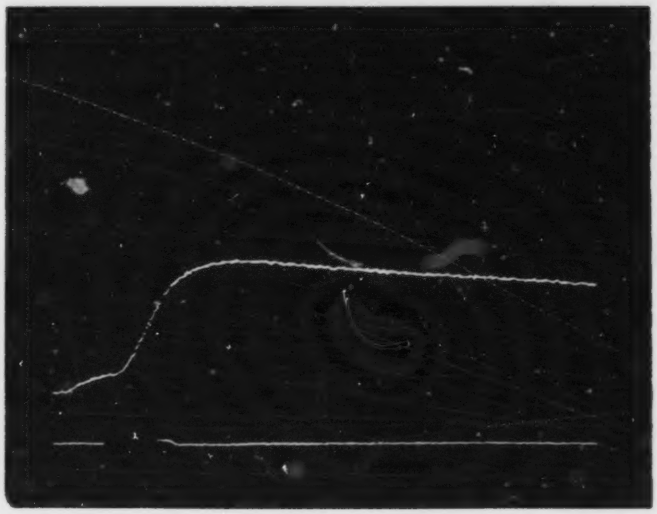


Coal Dust T. Ridge B.C.
Time Delay : 100 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 130
 (g/m3)
-(dp)comb : 2.729
 (psi)
-(dp/dt)max : 32.105
 (psi/sec)

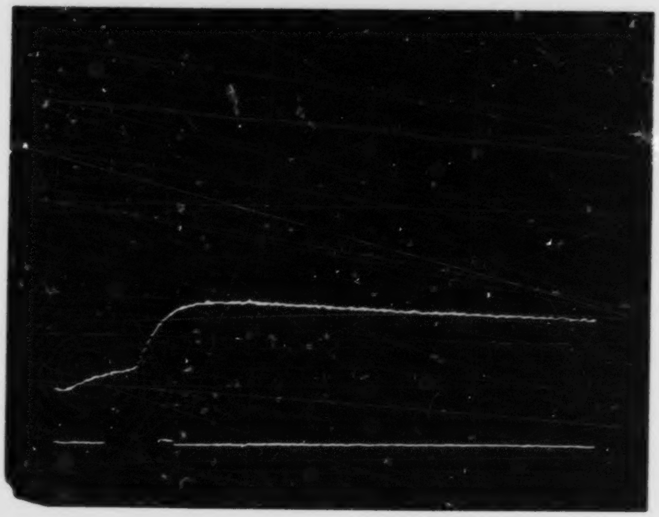


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 130
 (g/m3)
-(dp)comb : 3.899
 (psi)
-(dp/dt)max : 34.113
 (psi/sec)

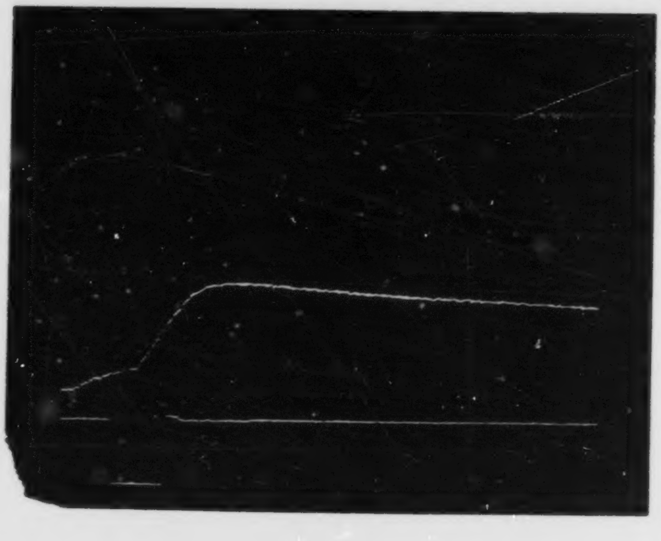


Coal Dust T. Ridge B.C.
Time Delay : 100 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 130
 (g/m3)
-(dp)comb : 2.534
 (psi)
-(dp/dt)max : 42.233
 (psi/sec)

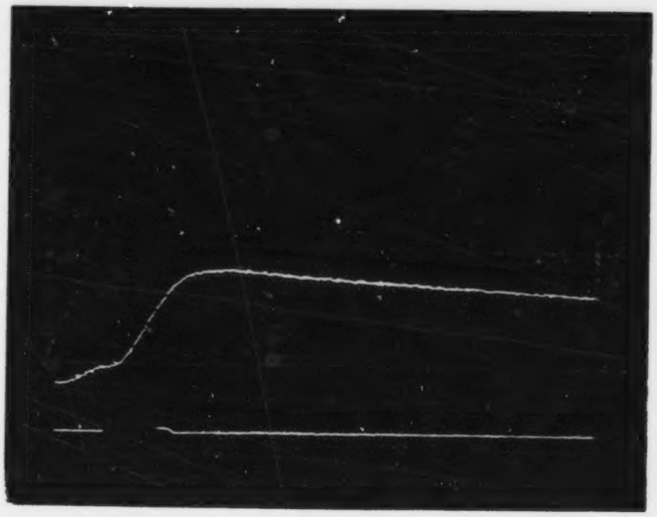


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 150
 (g/m3)
-(dp)comb : 3.119
 (psi)
-(dp/dt)max : 27.847
 (psi/sec)

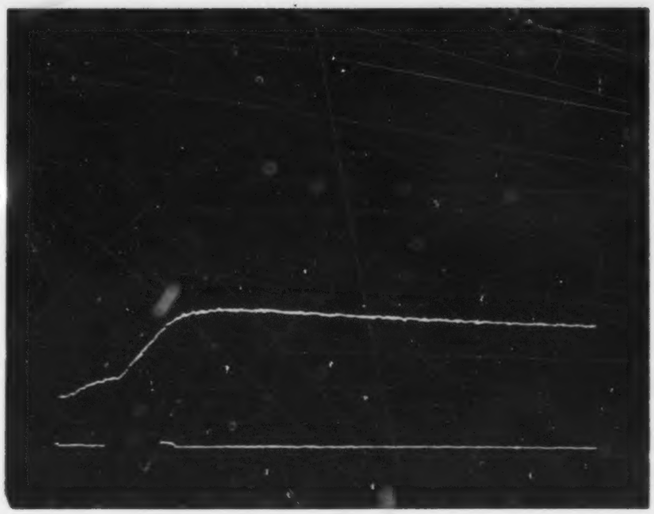


Coal Dust T. Ridge B.C.
Time Delay : 100 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 170
 (g/m3)
-(dp)comb : 3.142
 (psi)
-(dp/dt)max : 27.847
 (psi/sec)

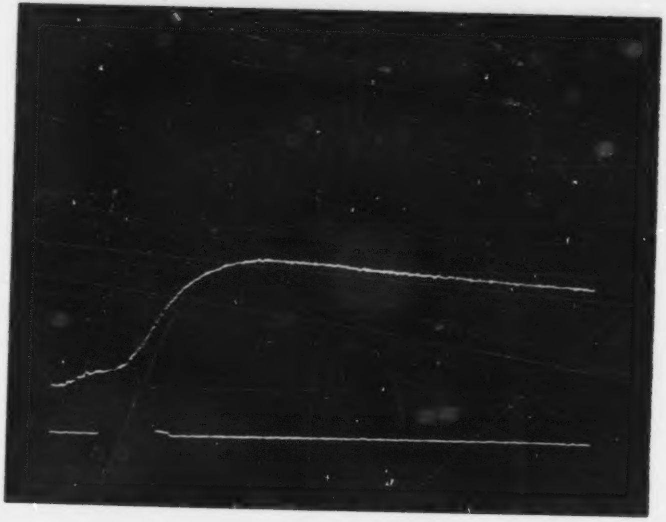


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 200
 (g/m3)
-(dp)comb : 2.534
 (psi)
-(dp/dt)max : 19.493
 (psi/sec)

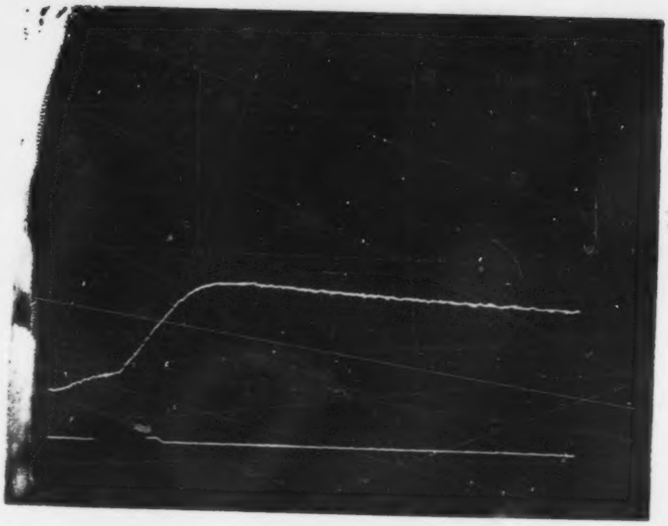


Coal Dust T. Ridge B.C.
Time Delay : 100 miliseconds

- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.1 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 210 (g/m3)
- -(dp)comb : 3.899 (psi)
- -(dp/dt)max : 29.240 (psi/sec)

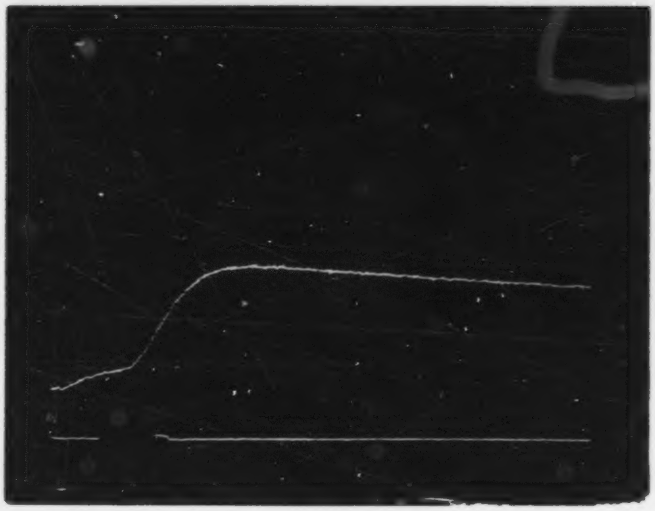


- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.1 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 230 (g/m3)
- -(dp)comb : 3.509 (psi)
- -(dp/dt)max : 27.847 (psi/sec)

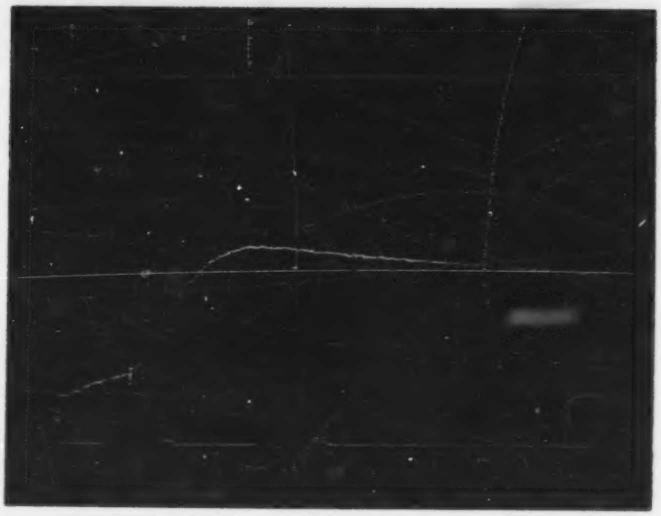


Coal Dust T. Ridge B.C.
Time Delay : 100 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 250
 (g/m3)
-(dp)comb : 3.704
 (psi)
-(dp/dt)max : 29.989
 (psi/sec)

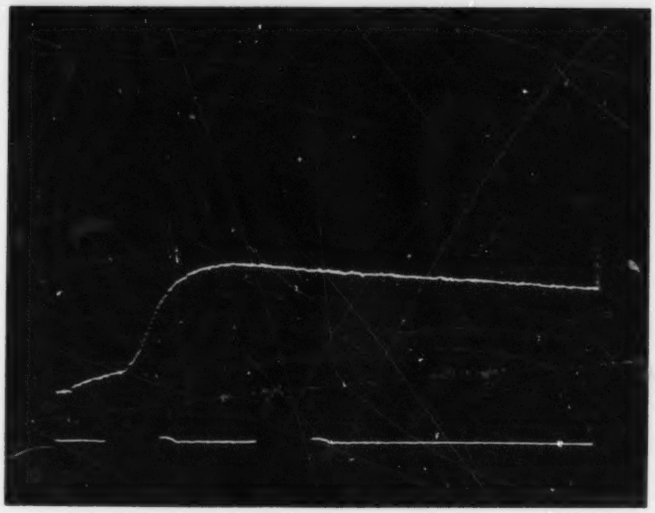


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 270
 (g/m3)
-(dp)comb : 4.094
 (psi)
-(dp/dt)max : 29.989
 (psi/sec)

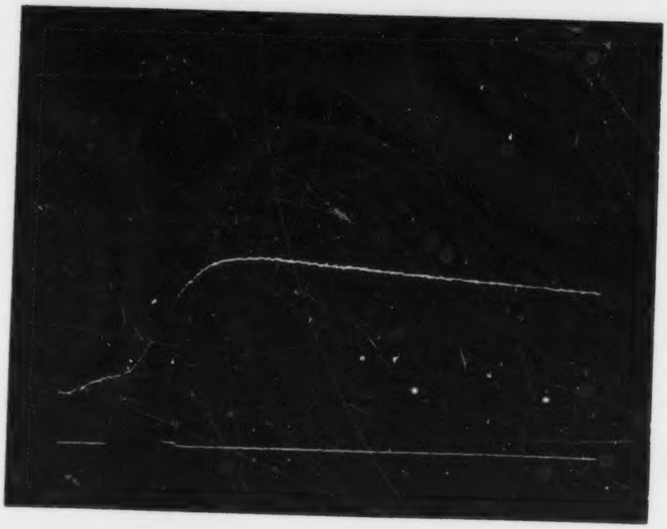


Coal Dust T. Ridge B.C.
Time Delay : 100 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 280
 (g/m3)
-(dp)comb : 3.889
 (psi)
-(dp/dt)max : 38.986
 (psi/sec)

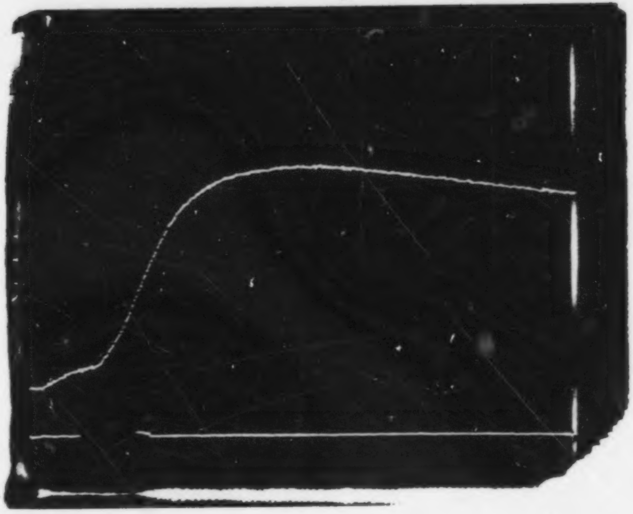


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 300
 (g/m3)
-(dp)comb : 4.288
 (psi)
-(dp/dt)max : 32.489
 (psi/sec)

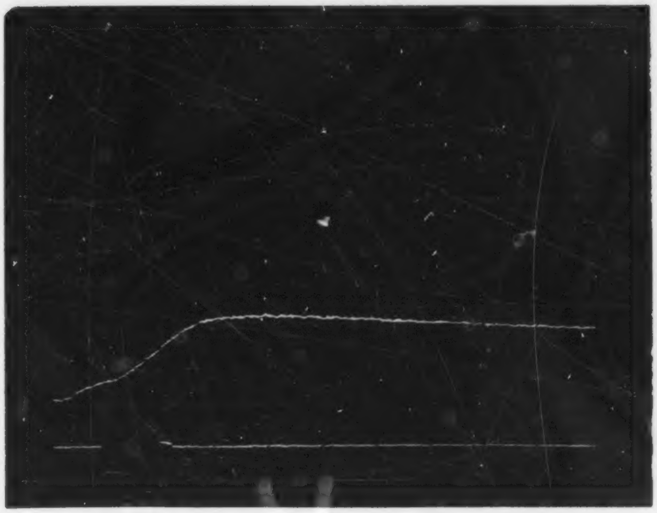


Coal Dust T. Ridge B.C.
Time Delay : 100 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 320
(g/m3)
-(dp)comb : 7.602
(psi)
-(dp/dt)max : 43.318
(psi/sec)

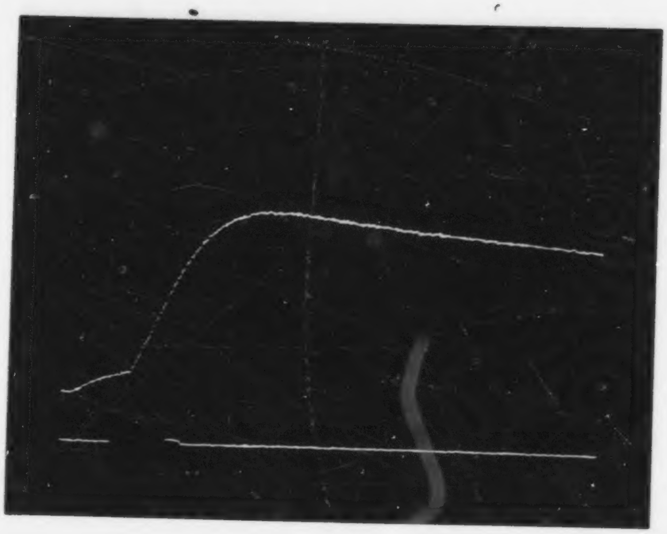


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 400
(g/m3)
-(dp)comb : 2.144
(psi)
-(dp/dt)max : 21.440
(psi/sec)



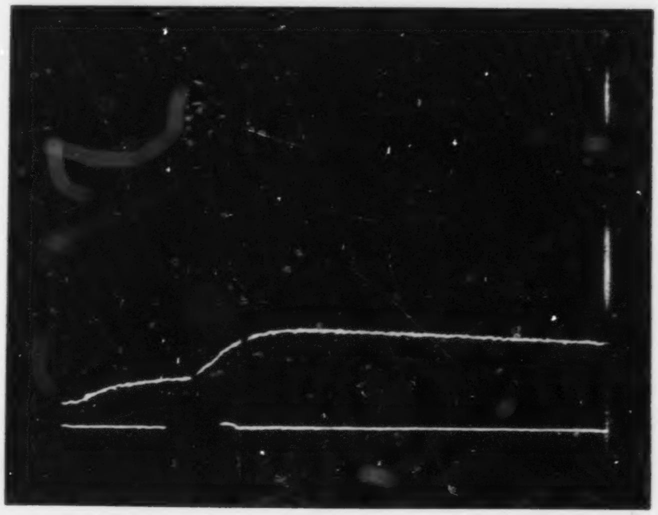
Coal Dust T. Ridge B.C.
Time Delay : 100 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 400
(g/m3)
-(dp)comb : 6.043
(psi)
-(dp/dt)max : 43.318
(psi/sec)

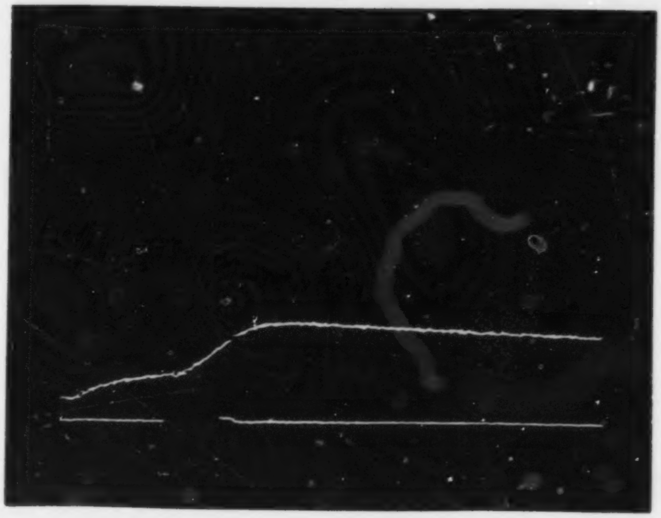


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 55
 (g/m3)
-(dp)comb : 1.754
 (psi)
-(dp/dt)max : 12.995
 (psi/sec)

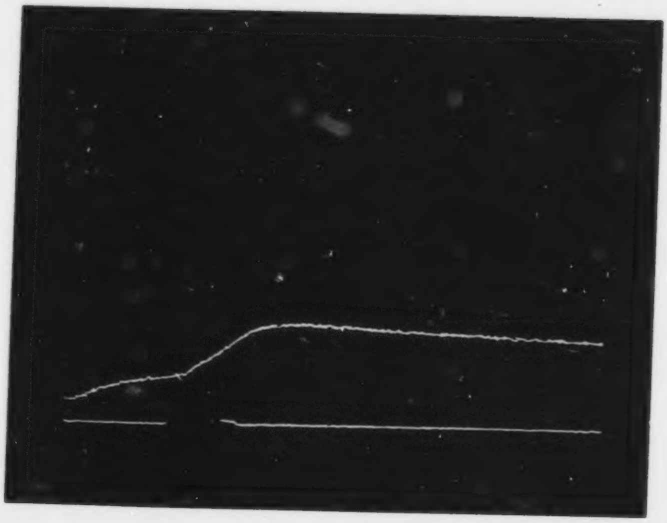


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 80
 (g/m3)
-(dp)comb : 1.754
 (psi)
-(dp/dt)max : 13.76
 (psi/sec)

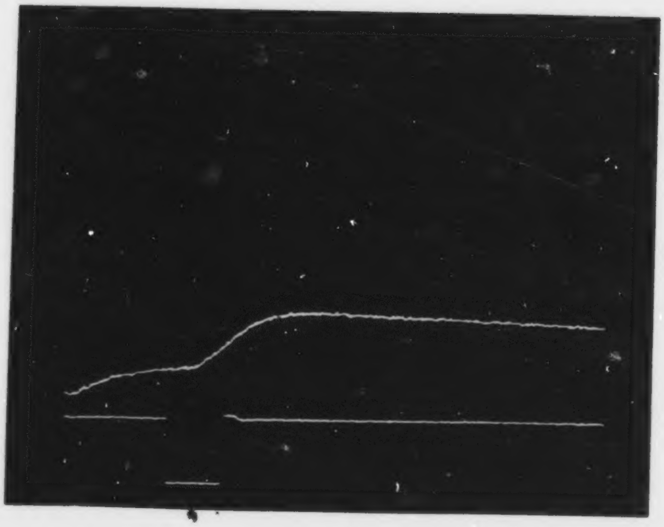


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 90
(g/m3)
-(dp)comb : 1.949
(psi)
-(dp/dt)max : 13.760
(psi/sec)

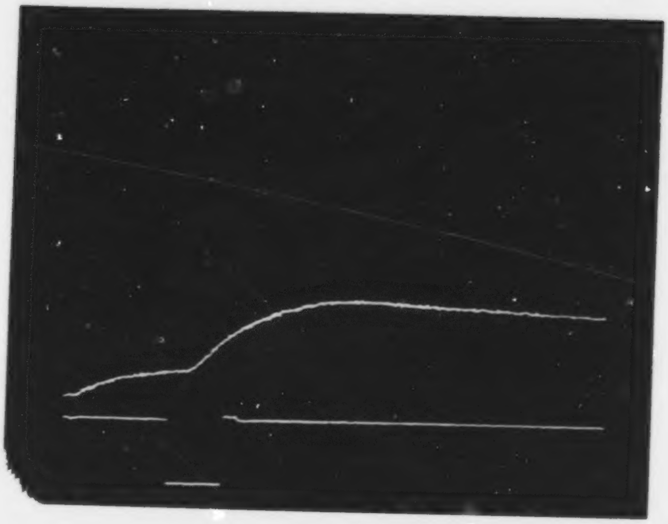


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 100
(g/m3)
-(dp)comb : 1.949
(psi)
-(dp/dt)max : 14.995
(psi/sec)

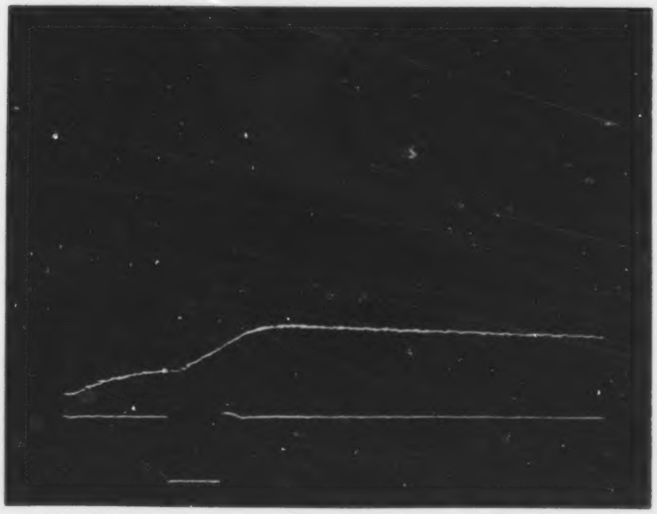


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 100
(g/m3)
-(dp)comb : 2.729
(psi)
-(dp/dt)max : 16.244
(psi/sec)

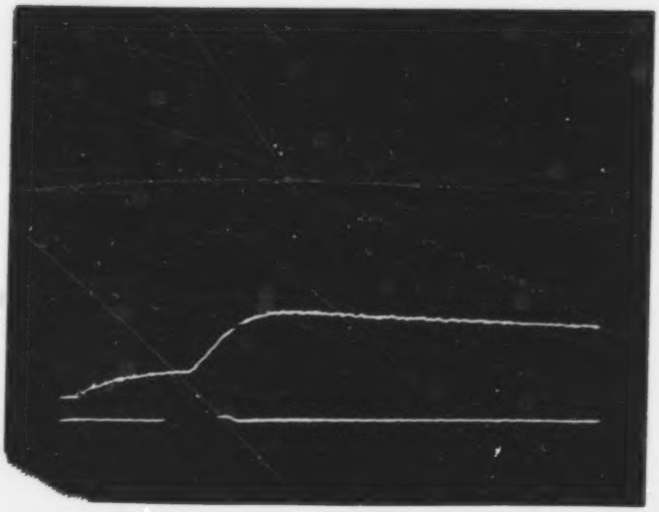


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 100
(g/m3)
-(dp)comb : 1.559
(psi)
-(dp/dt)max : 13.112
(psi/sec)

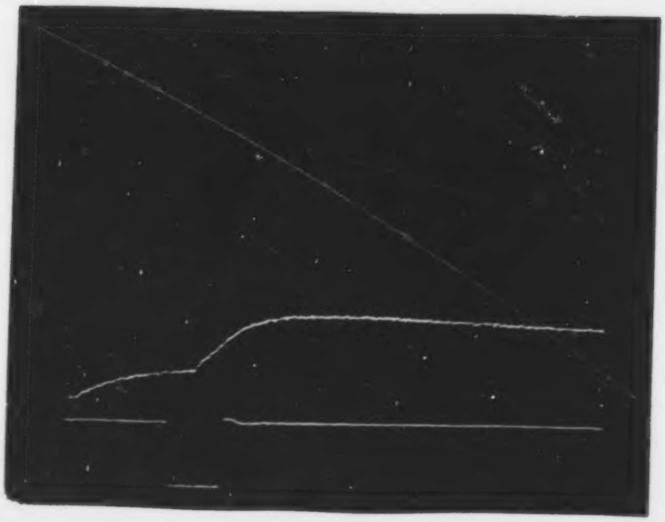


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.1 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 120 (g/m3)
- -(dp)comb : 2.144 (psi)
- -(dp/dt)max : 19.493 (psi/sec)

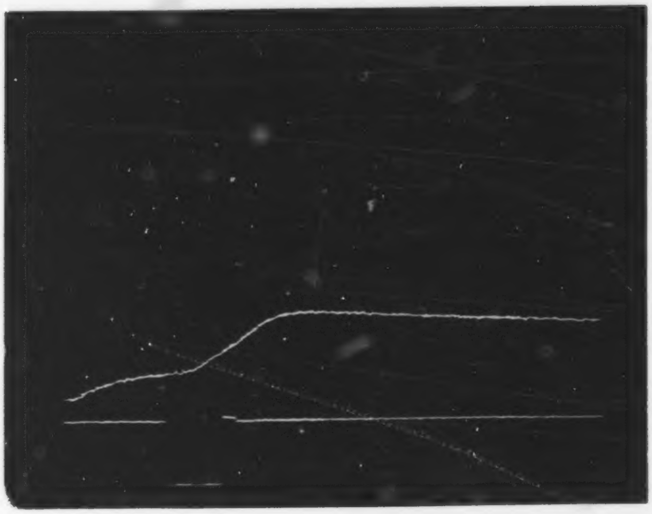


- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.1 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 120 (g/m3)
- -(dp)comb : 2.144 (psi)
- -(dp/dt)max : 17.327 (psi/sec)

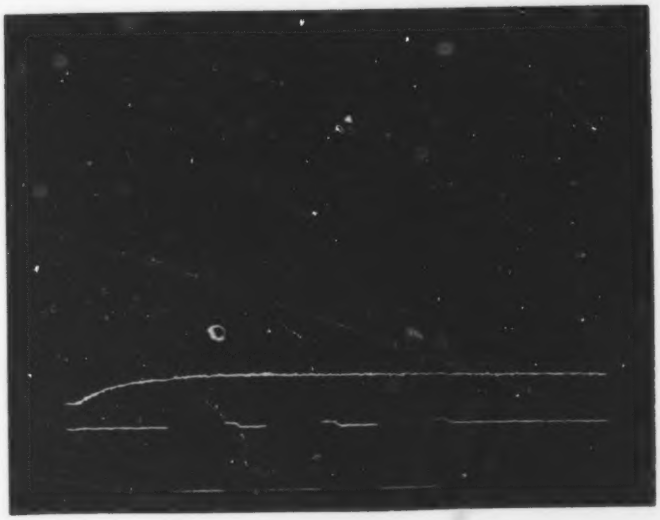


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 150
 (g/m3)
-(dp)comb : 1.949
 (psi)
-(dp/dt)max : 12.995
 (psi/sec)

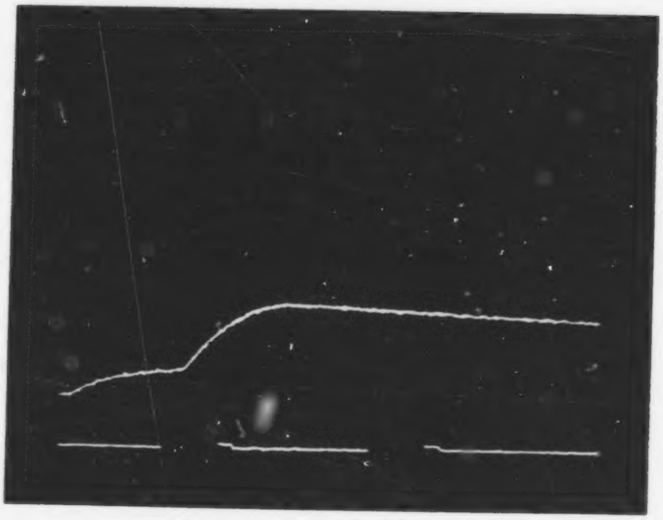


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 250
 (g/m3)
-(dp)comb : 0.974
 (psi)
-(dp/dt)max : 9.747
 (psi/sec)

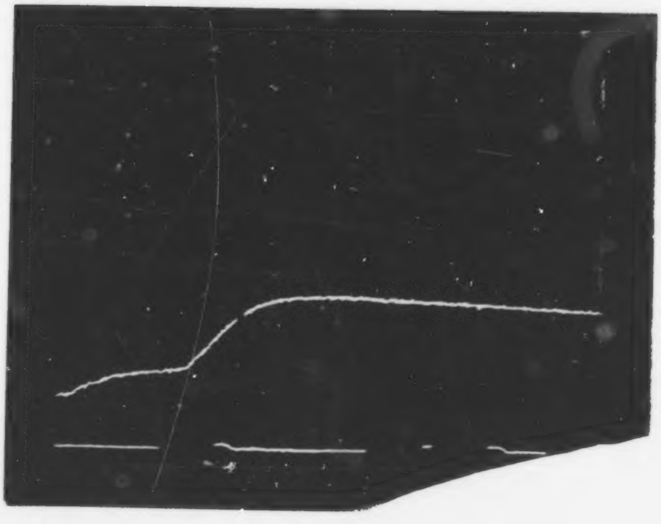


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 150
 (g/m3)
-(dp)comb : 2.534
 (psi)
-(dp/dt)max : 23.787
 (psi/sec)

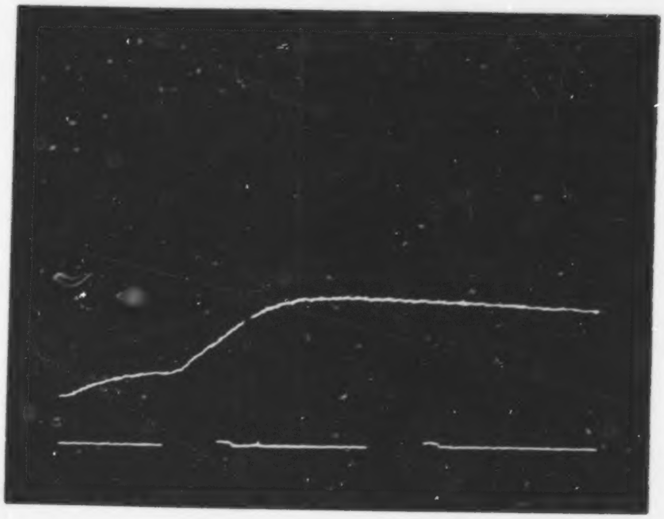


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 170
 (g/m3)
-(dp)comb : 2.729
 (psi)
-(dp/dt)max : 21.450
 (psi/sec)

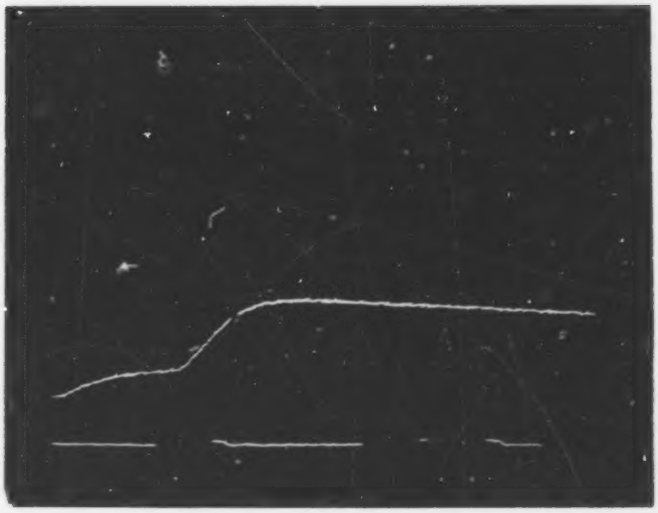


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 200
 (g/m3)
-(dp)comb : 2.729
 (psi)
-(dp/dt)max : 16.088
 (psi/sec)

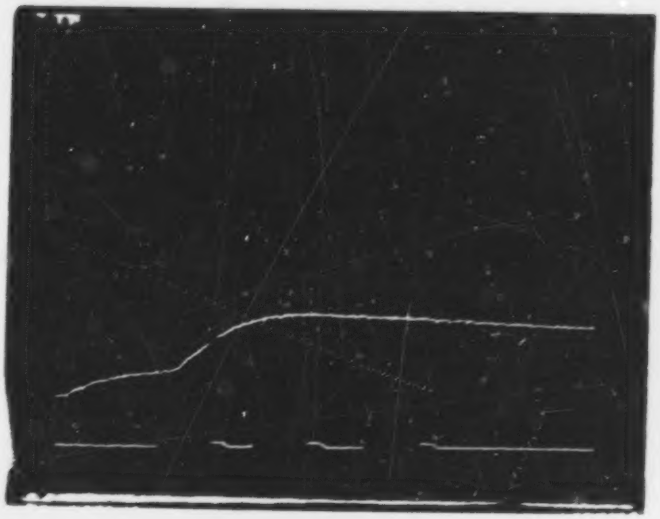


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 200
 (g/m3)
-(dp)comb : 2.534
 (psi)
-(dp/dt)max : 19.812
 (psi/sec)

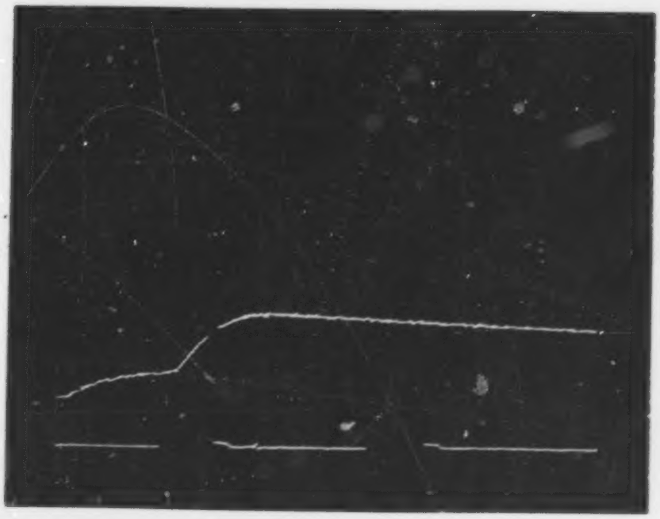


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 230
 (g/m3)
-(dp)comb : 2.144
 (psi)
-(dp/dt)max : 19.305
 (psi/sec)

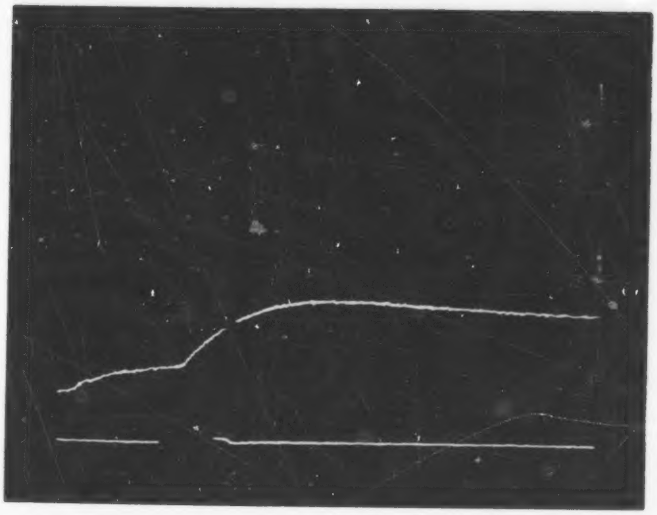


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 250
 (g/m3)
-(dp)comb : 2.144
 (psi)
-(dp/dt)max : 22.278
 (psi/sec)

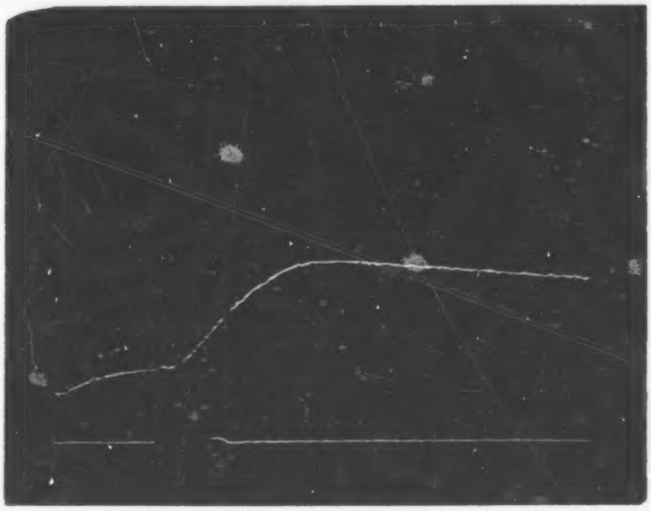


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.1 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 260 (g/m3)
- -(dp)comb : 2.340 (psi)
- -(dp/dt)max : 18.347 (psi/sec)

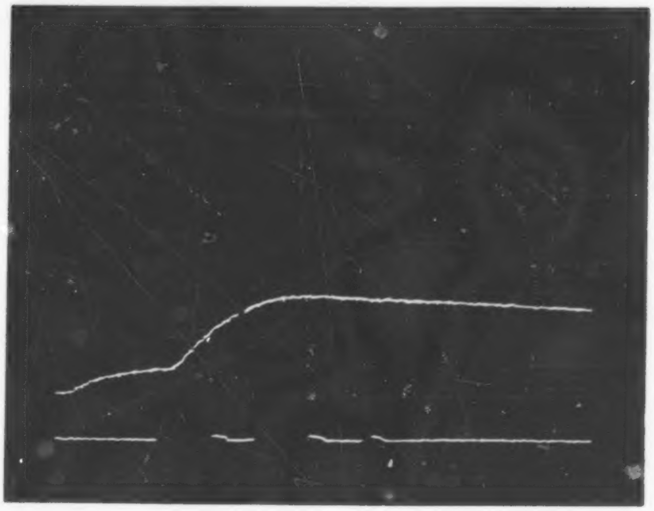


- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.1 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 260 (g/m3)
- -(dp)comb : 3.899 (psi)
- -(dp/dt)max : 22.711 (psi/sec)

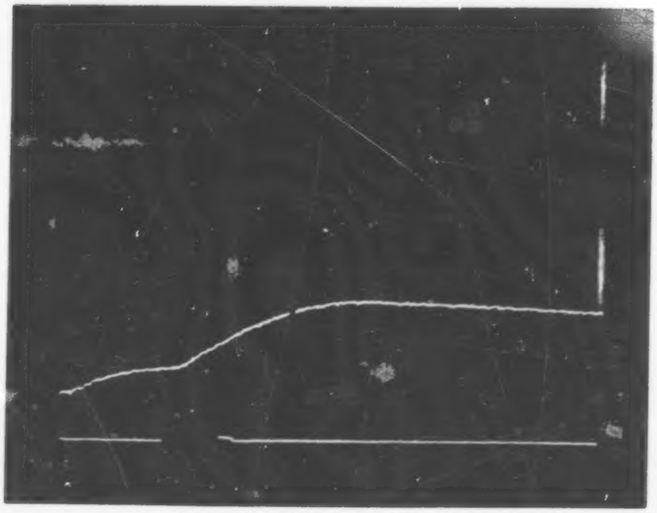


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

- -Dispersion
 Pressure : 200 psig
- -Electric Match 1.2g
 Black Powder
- -Po : 1 atm
- -Time Scale: 0.1
 (sec/div)
- -Pressure Scale: 10
 (psi/div)
- -Concentration: 280
 (g/m3)
- -(dp)comb : 2.729
 (psi)
- -(dp/dt)max : 16.244
 (psi/sec)

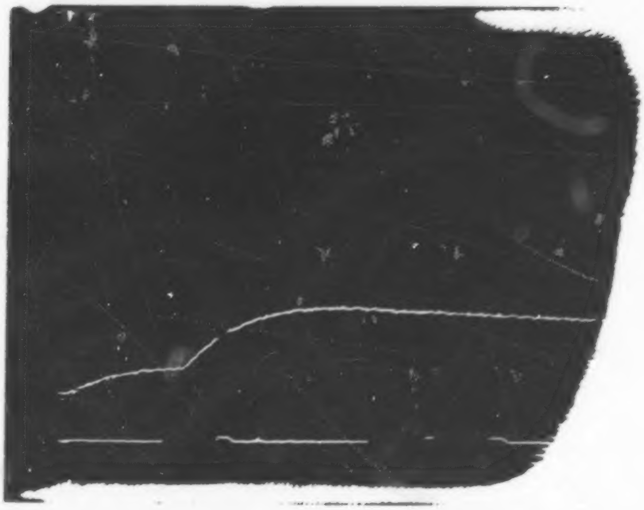


- -Dispersion
 Pressure : 200 psig
- -Electric Match 1.2g
 Black Powder
- -Po : 1 atm
- -Time Scale: 0.1
 (sec/div)
- -Pressure Scale: 10
 (psi/div)
- -Concentration: 300
 (g/m3)
- -(dp)comb : 2.339
 (psi)
- -(dp/dt)max : 9.747
 (psi/sec)

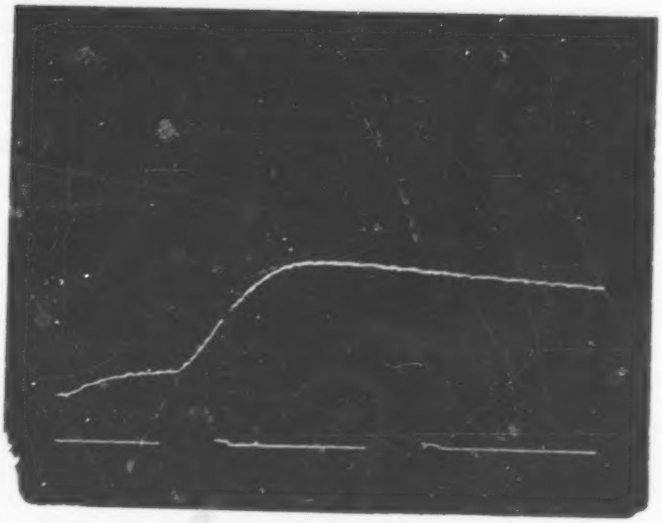


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 300
(g/m3)
-(dp)comb : 2.144
(psi)
-(dp/dt)max : 16.708
(psi/sec)

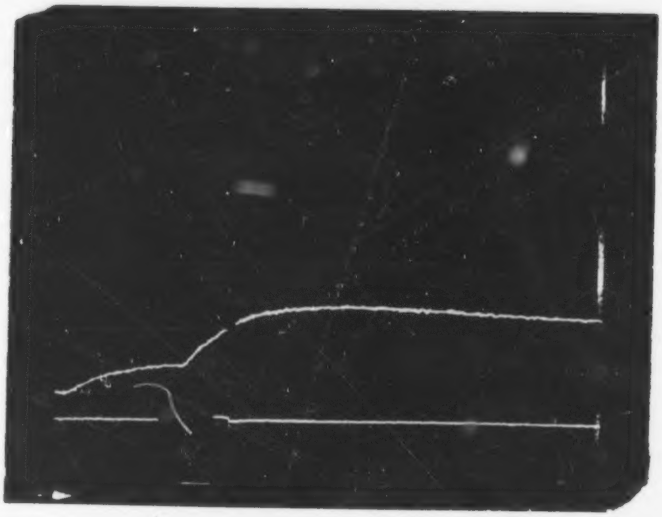


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 300
(g/m3)
-(dp)comb : 3.899
(psi)
-(dp/dt)max : 24.131
(psi/sec)

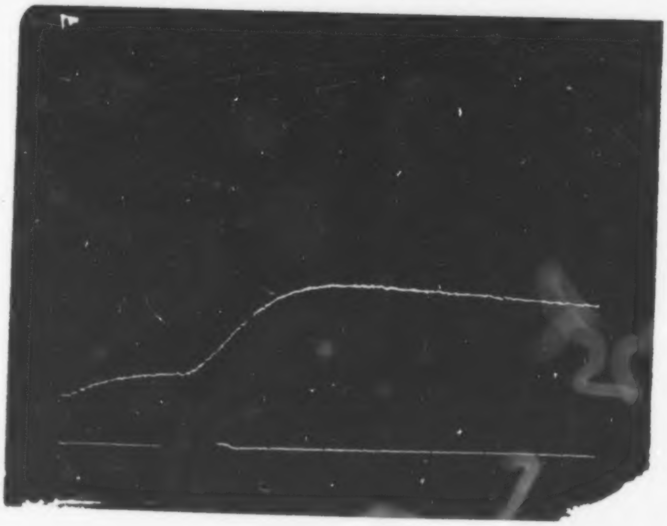


Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

- Dispersion Pressure : 200 psig
- Electric Match 1.2g Black Powder
- Po : 1 atm
- Time Scale: 0.1 (sec/div)
- Pressure Scale: 10 (psi/div)
- Concentration: 350 (g/m3)
- (dp)comb : 2.339 (psi)
- (dp/dt)max : 18.347 (psi/sec)

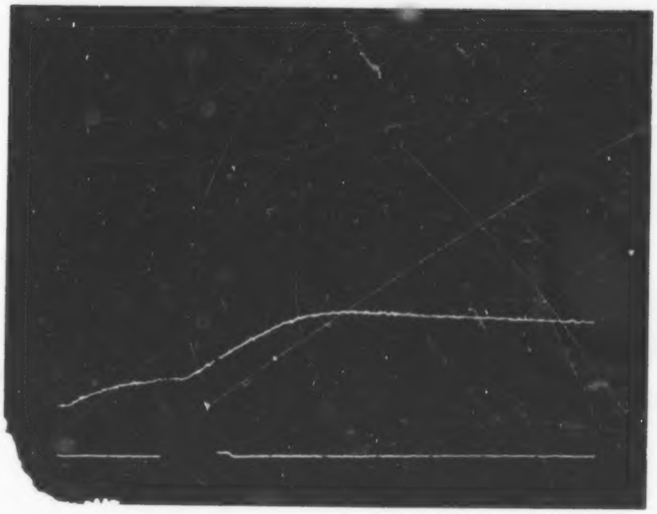


- Dispersion Pressure : 200 psig
- Electric Match 1.2g Black Powder
- Po : 1 atm
- Time Scale: 0.1 (sec/div)
- Pressure Scale: 10 (psi/div)
- Concentration: 350 (g/m3)
- (dp)comb : 3.185 (psi)
- (dp/dt)max : 19.493 (psi/sec)



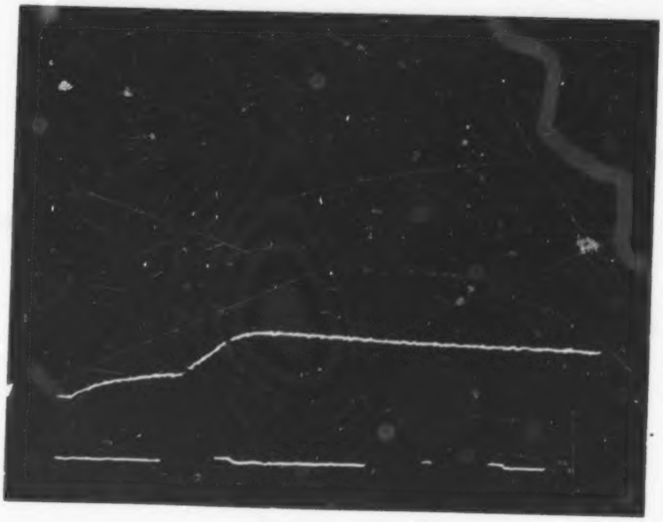
Coal Dust T. Ridge B.C.
Time Delay : 200 miliseconds

- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.1 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 500 (g/m3)
- -(dp)comb : 2.339 (psi)
- -(dp/dt)max : 12.183 (psi/sec)

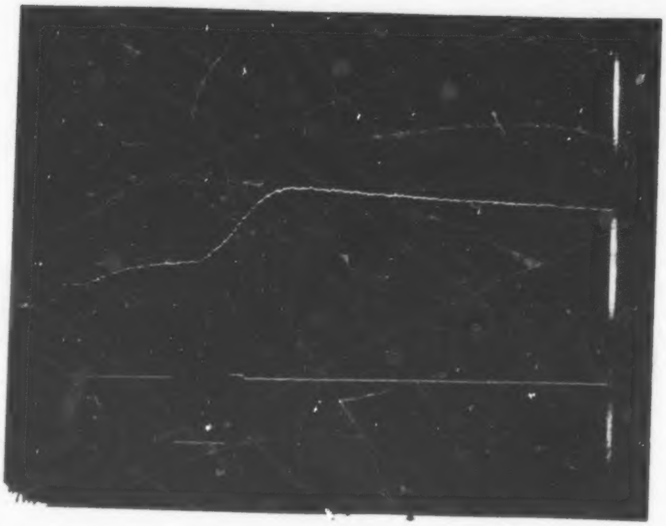


Cornstarch
Time Delay : 200 miliseconds

- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.1 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 70 (g/m3)
- -(dp)comb : 1.559 (psi)
- -(dp/dt)max : 13.924 (psi/sec)

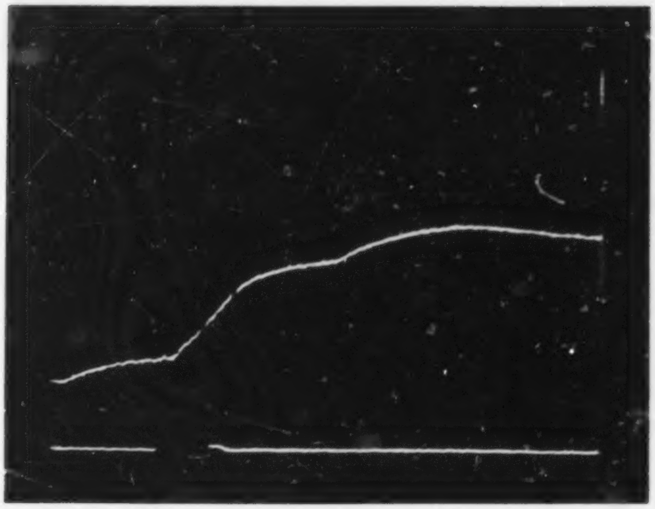


- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.1 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 75 (g/m3)
- -(dp)comb : 2.729 (psi)
- -(dp/dt)max : 25.990 (psi/sec)

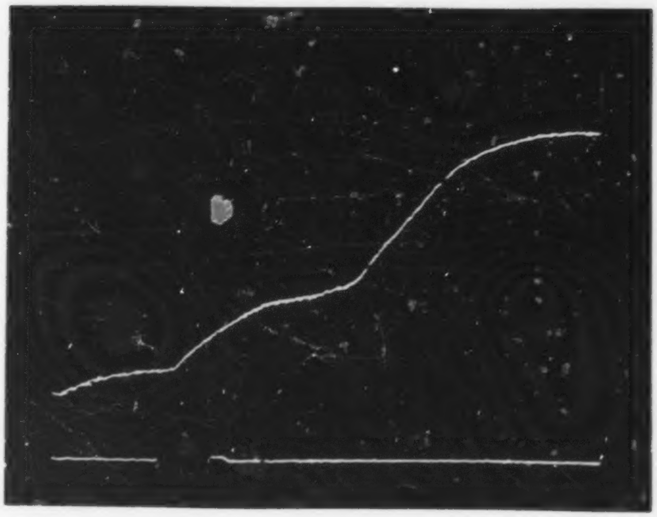


Cornstarch
Time Delay : 200 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 75
 (g/m3)
-(dp)comb : 6.823
 (psi)
-(dp/dt)max : 21.118
 (psi/sec)

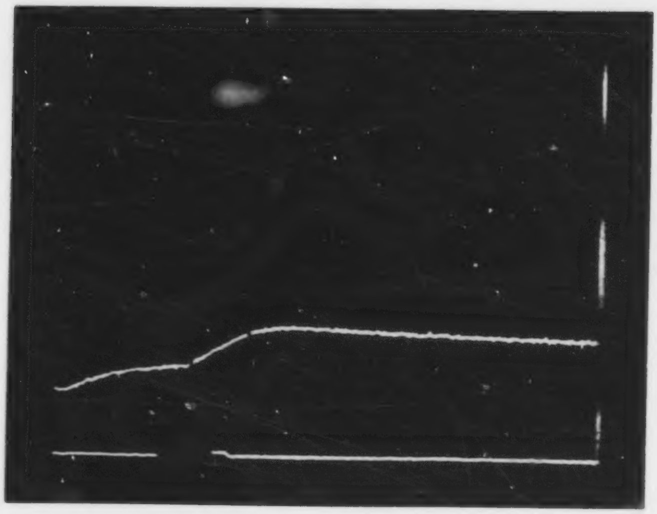


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 75
 (g/m3)
-(dp)comb : 8.576
 (psi)
-(dp/dt)max : 15.316
 (psi/sec)

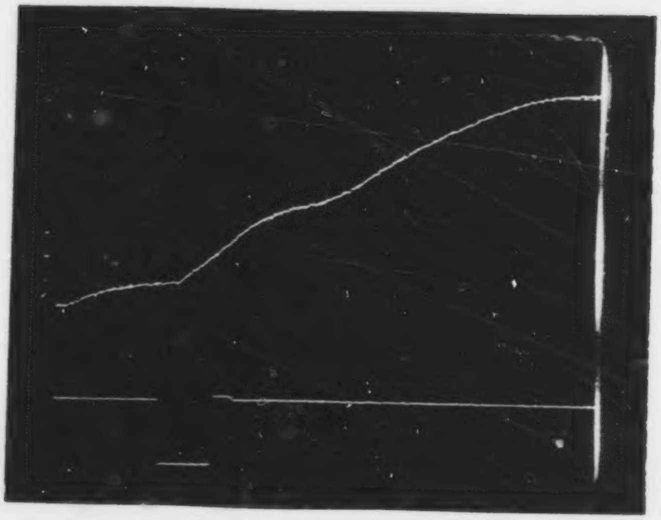


Cornstarch
Time Delay : 200 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 75
 (g/m3)
-(dp)comb : 1.559
 (psi)
-(dp/dt)max : 10.633
 (psi/sec)

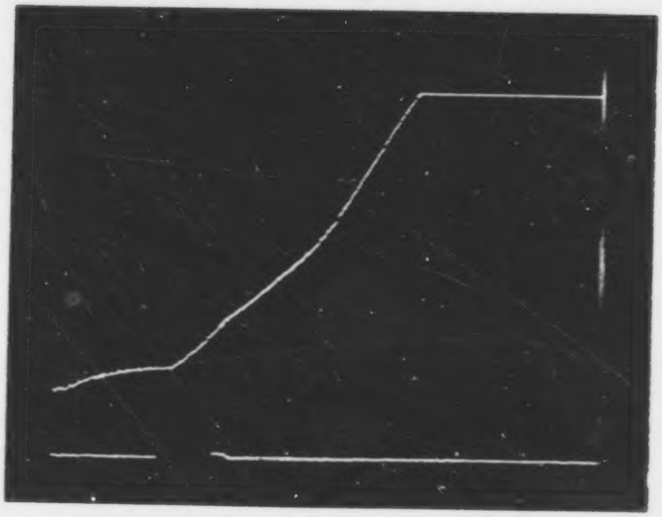


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 80
 (g/m3)
-(dp)comb : 6.823
 (psi)
-(dp/dt)max : 14.62
 (psi/sec)

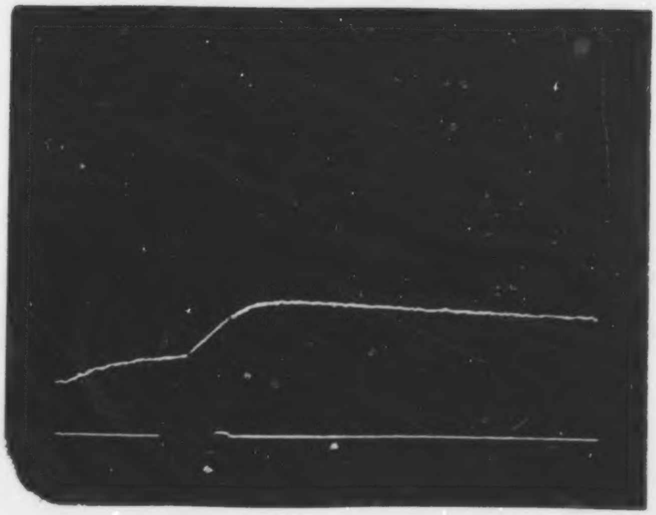


Cornstarch
Time Delay : 200 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 80
(g/m3)
-(dp)comb : 9.746
(psi)
-(dp/dt)max : 37.362
(psi/sec)

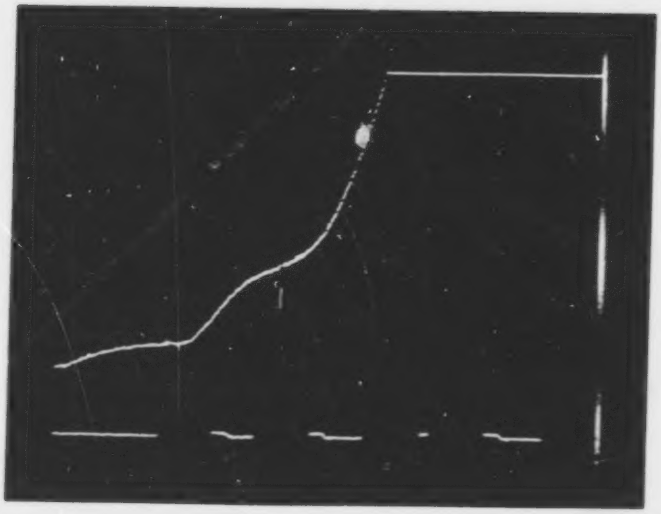


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 80
(g/m3)
-(dp)comb : 1.949
(psi)
-(dp/dt)max : 17.057
(psi/sec)



Cornstarch
Time Delay : 200 miliseconds

- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.1 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 90 (g/m3)
- -(dp)comb : 9.746 (psi)
- -(dp/dt)max : 58.480 (psi/sec)



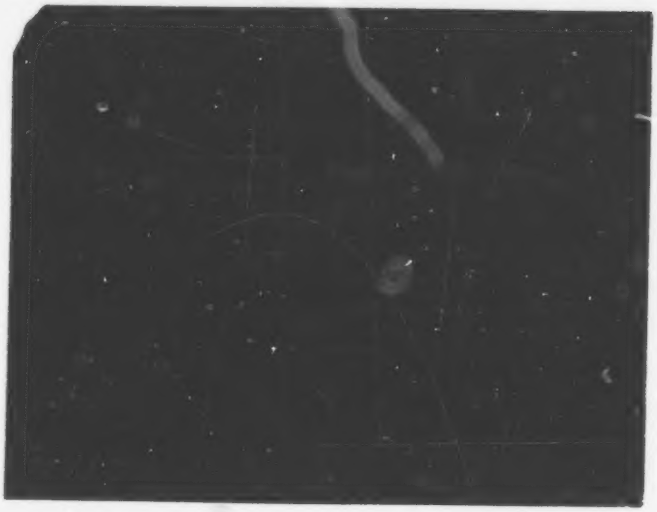
Cornstarch
Time Delay : 300 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 70
(g/m3)
-(dp)comb : 2.339
(psi)
-(dp/dt)max : 21.659
(psi/sec)

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 75
(g/m3)
-(dp)comb : 2.339
(psi)
-(dp/dt)max : 16.244
(psi/sec)

Cornstarch
Time Delay : 300 miliseconds

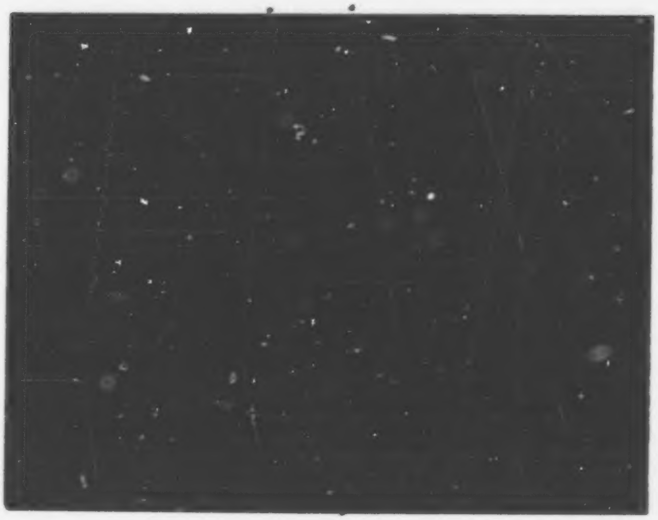
-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 80
(g/m3)
-(dp)comb : 2.830
(psi)
-(dp/dt)max : 19.493
(psi/sec)



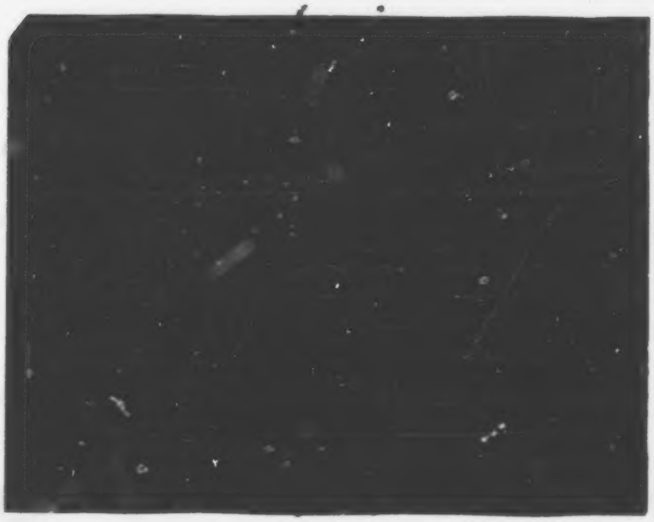
-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 80
(g/m3)
-(dp)comb : 7.790
(psi)
-(dp/dt)max : 32.489
(psi/sec)

Cornstarch
Time Delay : 300 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 80
 (g/m3)
-(dp)comb : 2.720
 (psi)
-(dp/dt)max : 25.991
 (psi/sec)

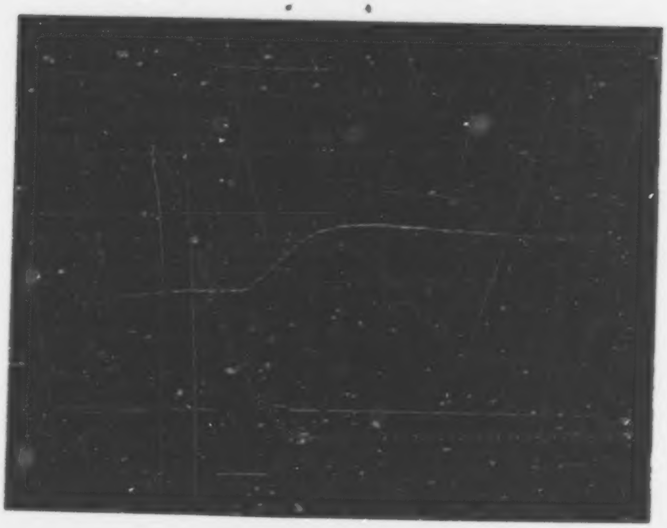


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 80
 (g/m3)
-(dp)comb : 5.458
 (psi)
-(dp/dt)max : 16.244
 (psi/sec)

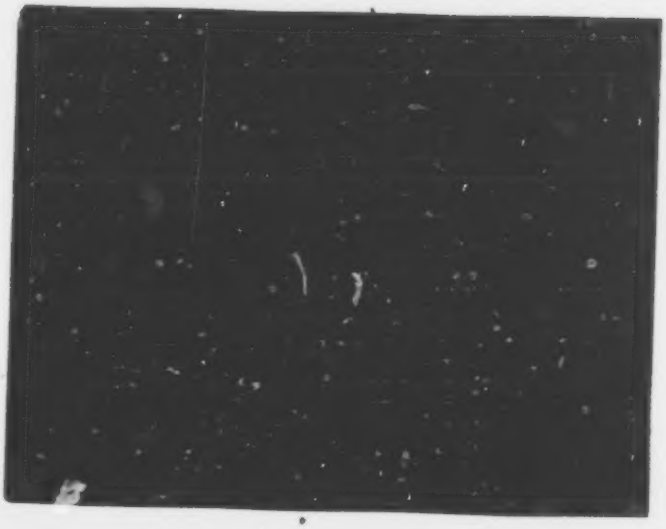


Cornstarch
Time Delay : 300 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 80
 (g/m3)
-(dp)comb : 2.339
 (psi)
-(dp/dt)max : 19.49
 (psi/sec)



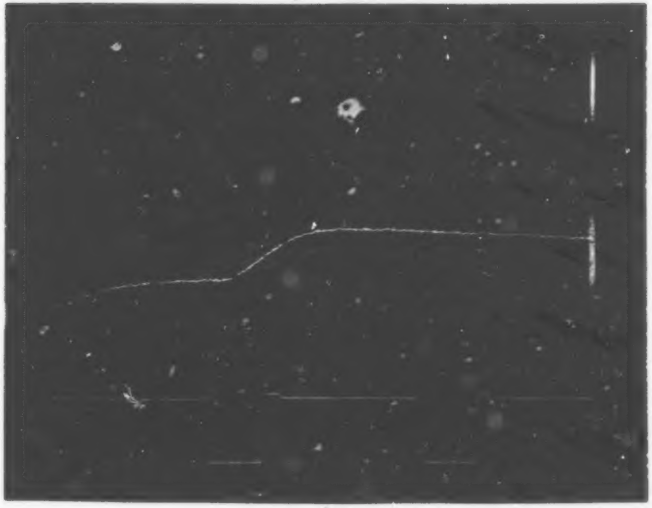
-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 85
 (g/m3)
-(dp)comb : 3.700
 (psi)
-(dp/dt)max : 22.933
 (psi/sec)



Cornstarch
Time Delay : 300 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 90
 (g/m3)
-(dp)comb : 3.509
 (psi)
-(dp/dt)max : 21.659
 (psi/sec)

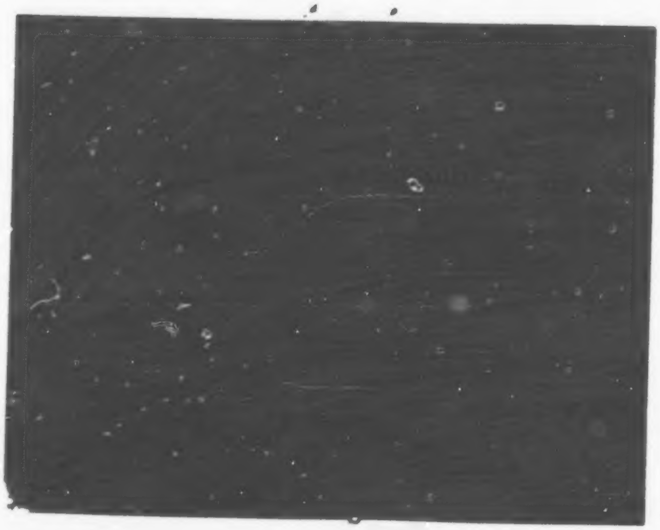
-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 90
 (g/m3)
-(dp)comb : 1.754
 (psi)
-(dp/dt)max : 11.700
 (psi/sec)



Cornstarch
Time Delay : 300 miliseconds

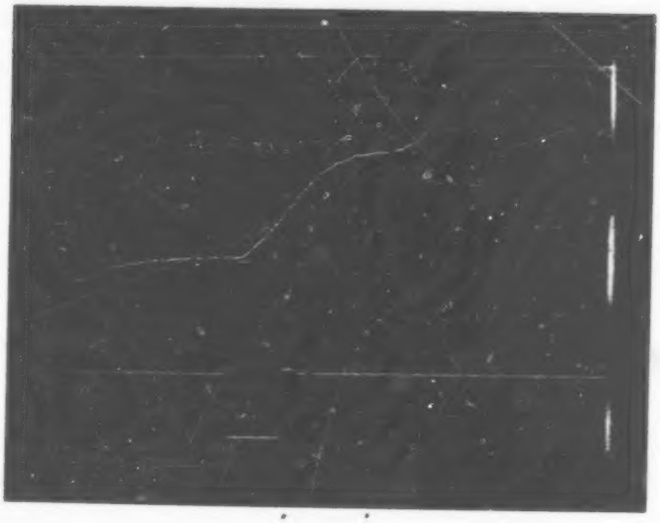
-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 90
(g/m3)
-(dp)comb : 2.339
(psi)
-(dp/dt)max : 22.280
(psi/sec)

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 90
(g/m3)
-(dp)comb : 2.924
(psi)
-(dp/dt)max : 17.540
(psi/sec)

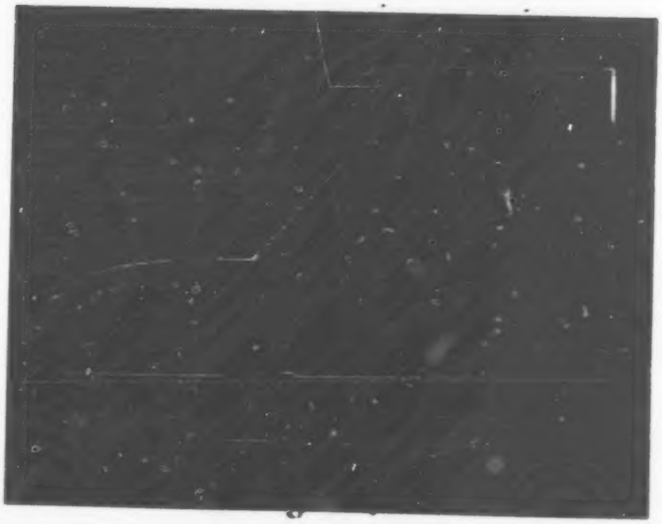


Cornstarch
Time Delay : 300 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 95
 (g/m3)
-(dp)comb : 6.823
 (psi)
-(dp/dt)max : 35.740
 (psi/sec)

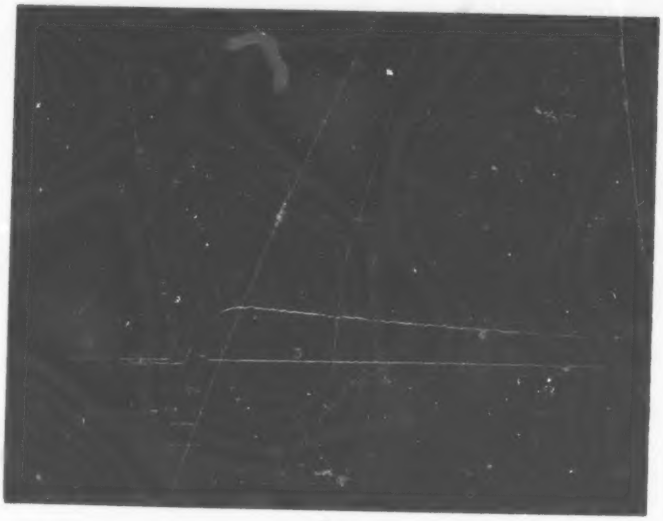


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 100
 (g/m3)
-(dp)comb : 6.823
 (psi)
-(dp/dt)max : 48.730
 (psi/sec)

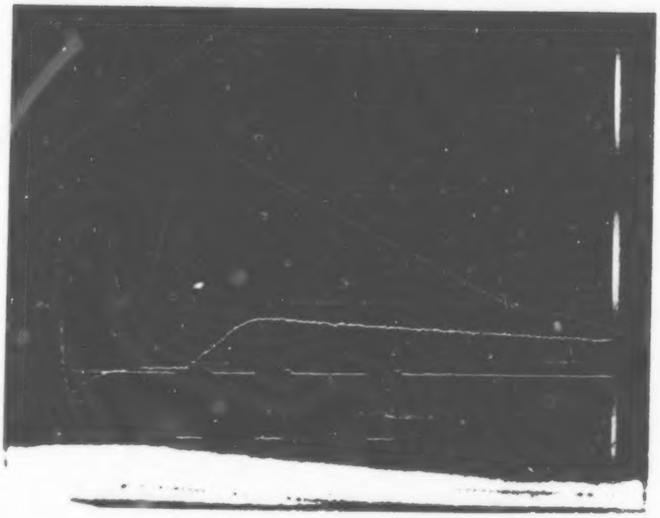


Cornstarch
Time Delay : 400 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 60
(g/m3)
-(dp)comb : 1.949
(psi)
-(dp/dt)max : 27.847
(psi/sec)

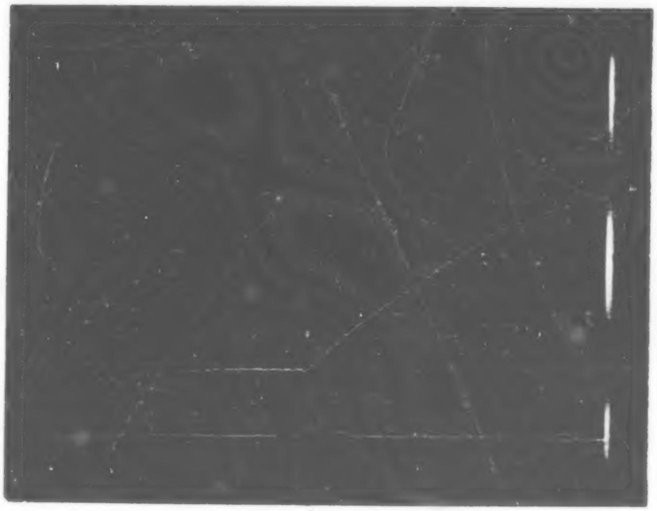


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 65
(g/m3)
-(dp)comb : 1.949
(psi)
-(dp/dt)max : 19.493
(psi/sec)

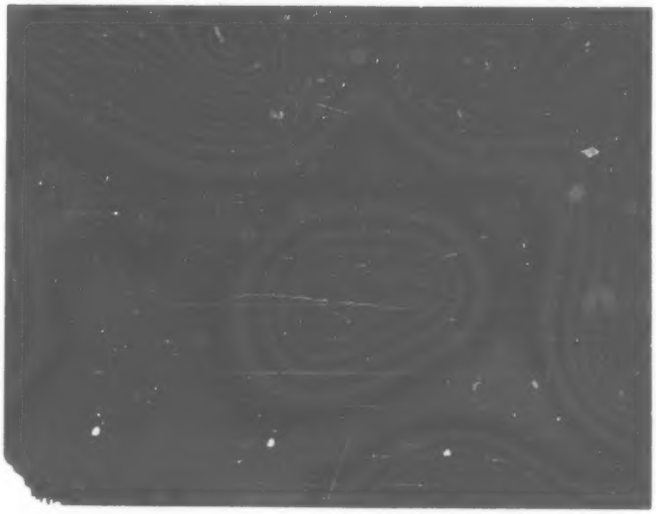


Cornstarch
Time Delay : 400 miliseconds

- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.1 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 70 (g/m3)
- -(dp)comb : 5.848 (psi)
- -(dp/dt)max : 16.244 (psi/sec)

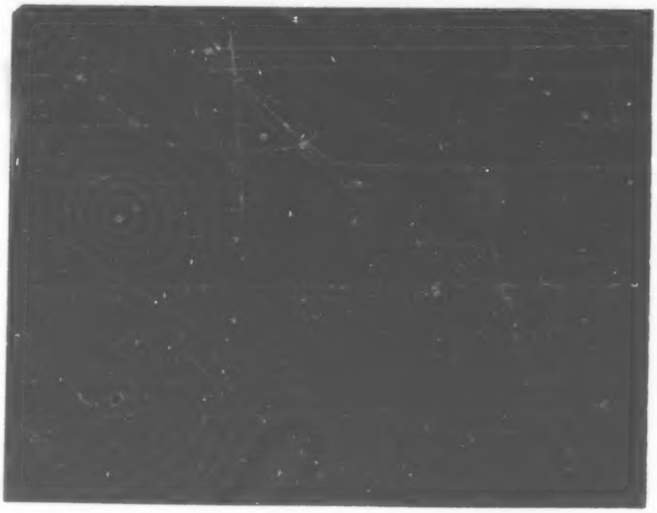


- -Dispersion Pressure : 200 psig
- -Electric Match 1.2g Black Powder
- -Po : 1 atm
- -Time Scale: 0.2 (sec/div)
- -Pressure Scale: 10 (psi/div)
- -Concentration: 70 (g/m3)
- -(dp)comb : 2.729 (psi)
- -(dp/dt)max : 38.986 (psi/sec)

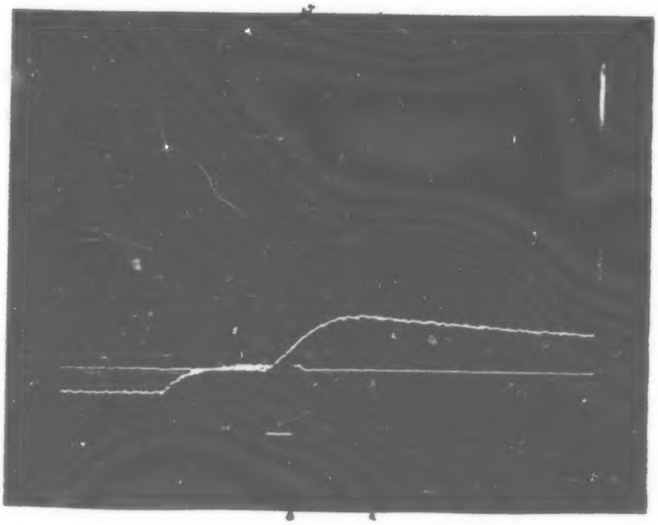


Cornstarch
Time Delay : 400 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 80
(g/m3)
-(dp)comb : 3.216
(psi)
-(dp/dt)max : 19.493
(psi/sec)



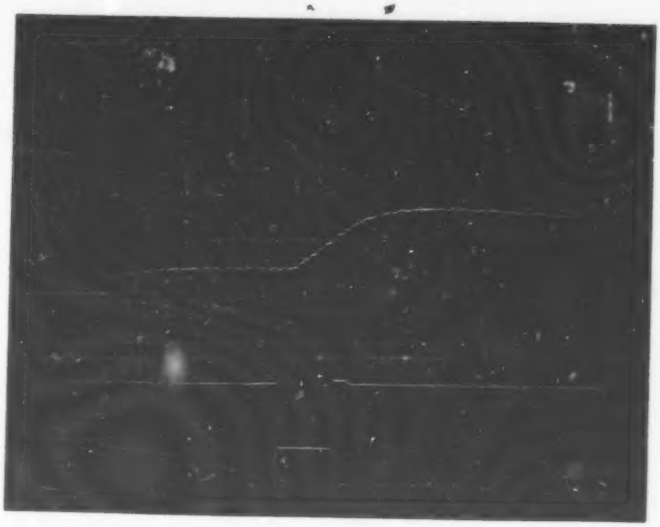
-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.1
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 80
(g/m3)
-(dp)comb : 1.949
(psi)
-(dp/dt)max : 19.493
(psi/sec)



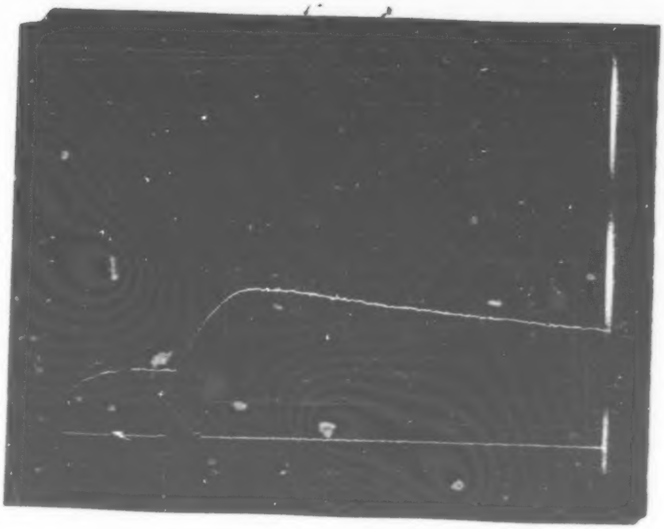
X

Cornstarch
Time Delay : 400 miliseconds

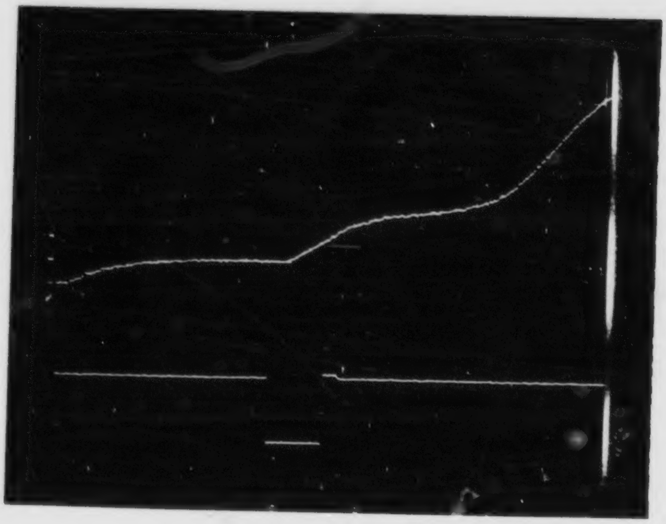
- Dispersion Pressure : 200 psig
- Electric Match 1.2g Black Powder
- Po : 1 atm
- Time Scale: 0.1 (sec/div)
- Pressure Scale: 10 (psi/div)
- Concentration: 90 (g/m3)
- (dp)comb : 2.339 (psi)
- (dp/dt)max : 13.924 (psi/sec)



- Dispersion Pressure : 200 psig
- Electric Match 1.2g Black Powder
- Po : 1 atm
- Time Scale: 0.2 (sec/div)
- Pressure Scale: 10 (psi/div)
- Concentration: 95 (g/m3)
- (dp)comb : 3.119 (psi)
- (dp/dt)max : 38.986 (psi/sec)



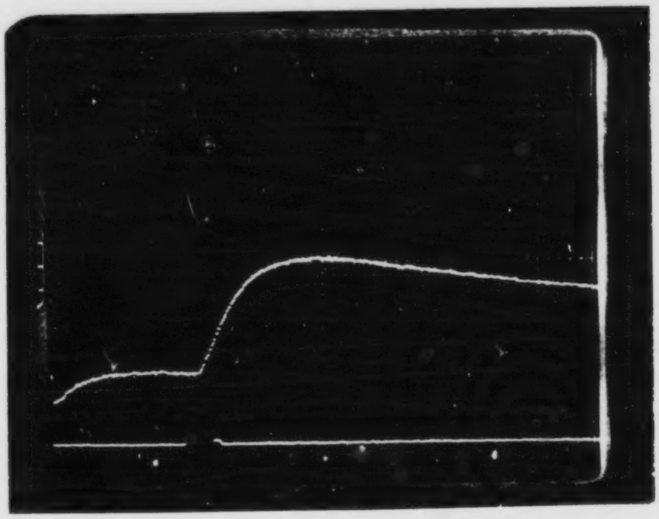
Cornstarch
Time Delay : 400 miliseconds



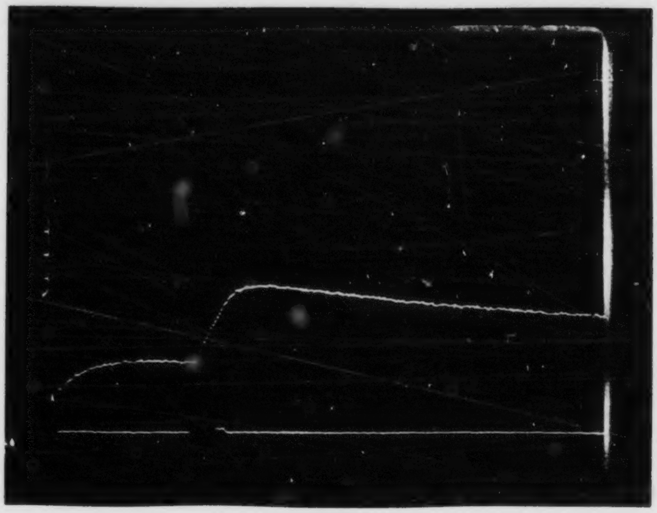
-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.1
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 100
 (g/m3)
-(dp)comb : 5.848
 (psi)
-(dp/dt)max : 21.659
 (psi/sec)

Cornstarch
Time Delay : 500 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 80
(g/m3)
-(dp)comb : 3.958
(psi)
-(dp/dt)max : 43.318
(psi/sec)

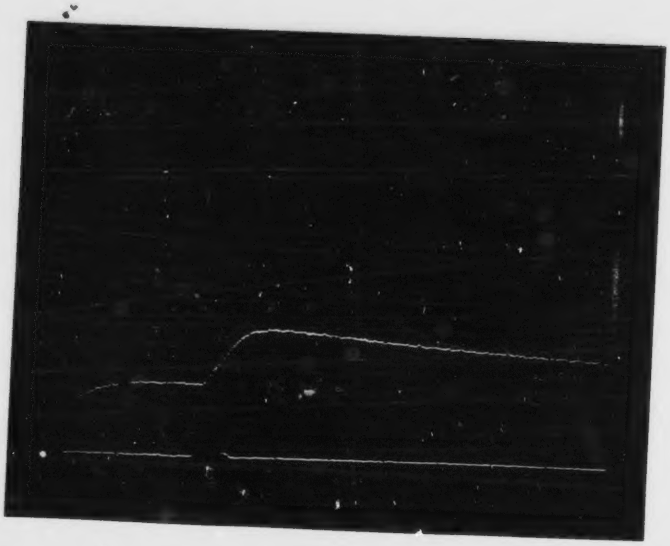


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 80
(g/m3)
-(dp)comb : 2.729
(psi)
-(dp/dt)max : 48.733
(psi/sec)

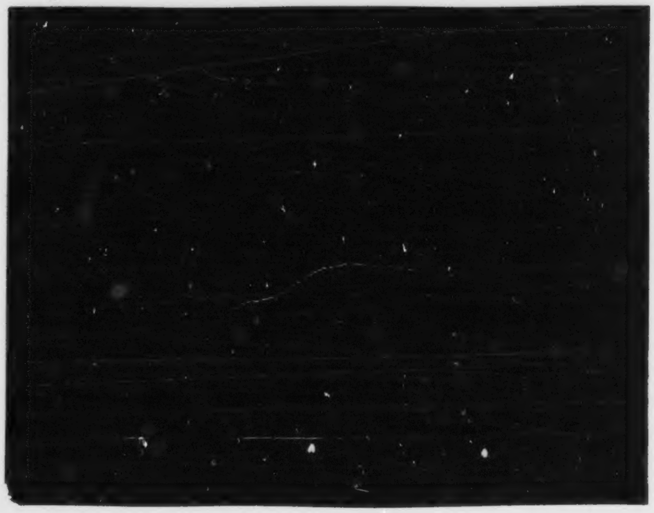


Cornstarch
Time Delay : 500 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 80
 (g/m3)
-(dp)comb : 1.949
 (psi)
-(dp/dt)max : 24.366
 (psi/sec)

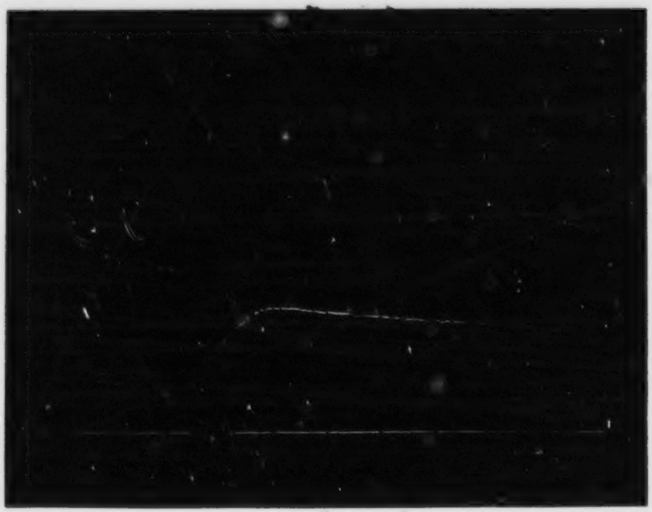


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 85
 (g/m3)
-(dp)comb : 3.704
 (psi)
-(dp/dt)max : 43.318
 (psi/sec)

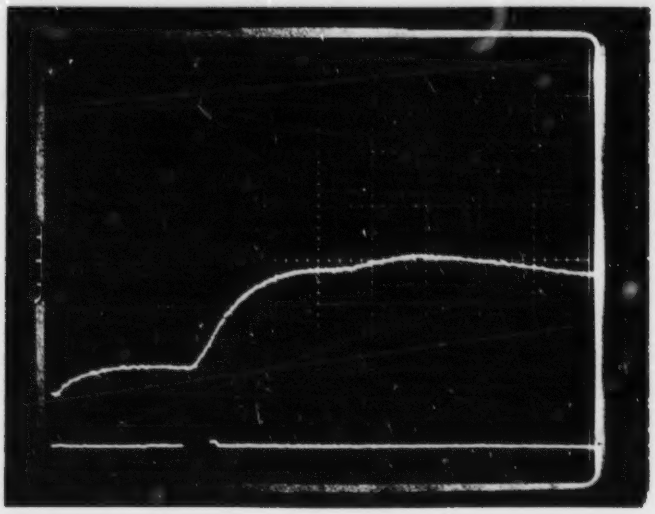


Cornstarch
Time Delay : 500 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 85
(g/m3)
-(dp)comb : 2.339
(psi)
-(dp/dt)max : 24.366
(psi/sec)

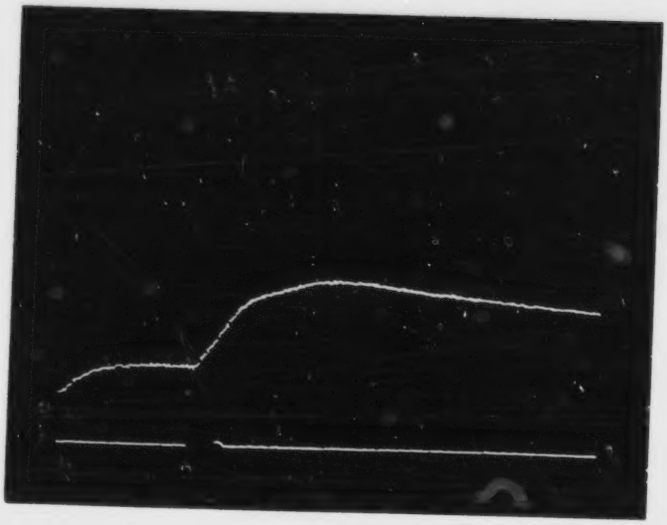


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 90
(g/m3)
-(dp)comb : 3.899
(psi)
-(dp/dt)max : 32.489
(psi/sec)

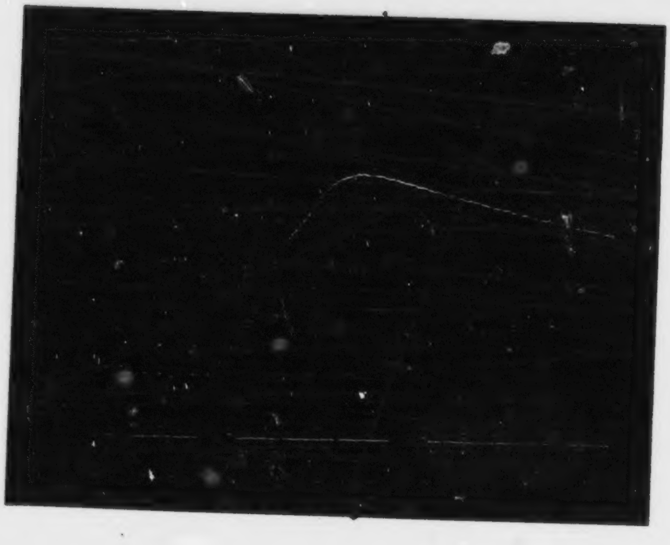


Cornstarch
Time Delay : 500 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 90
 (g/m3)
-(dp)comb : 3.119
 (psi)
-(dp/dt)max : 27.847
 (psi/sec)

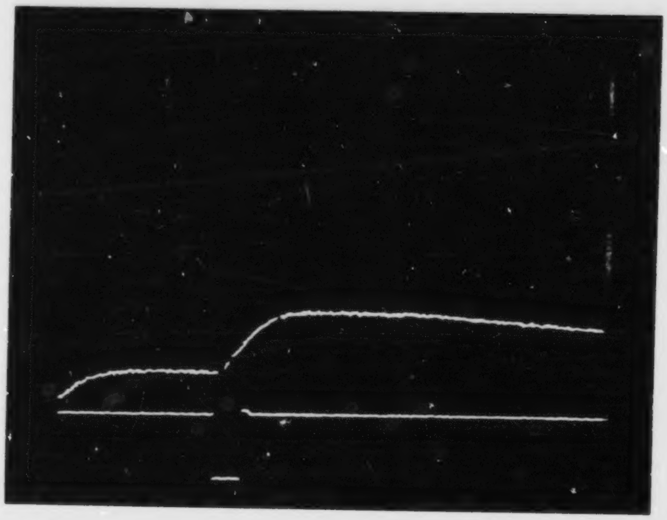


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 95
 (g/m3)
-(dp)comb : 7.212
 (psi)
-(dp/dt)max : 38.986
 (psi/sec)

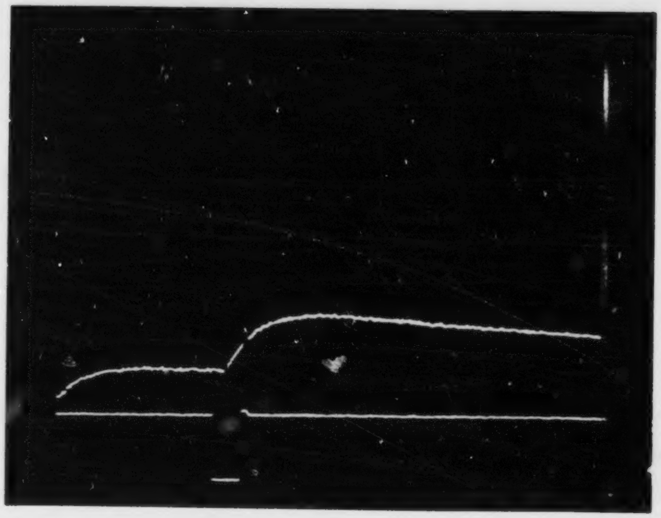


Cornstarch
Time Delay : 600 miliseconds

-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 80
 (g/m3)
-(dp)comb : 2.144
 (psi)
-(dp/dt)max : 14.620
 (psi/sec)

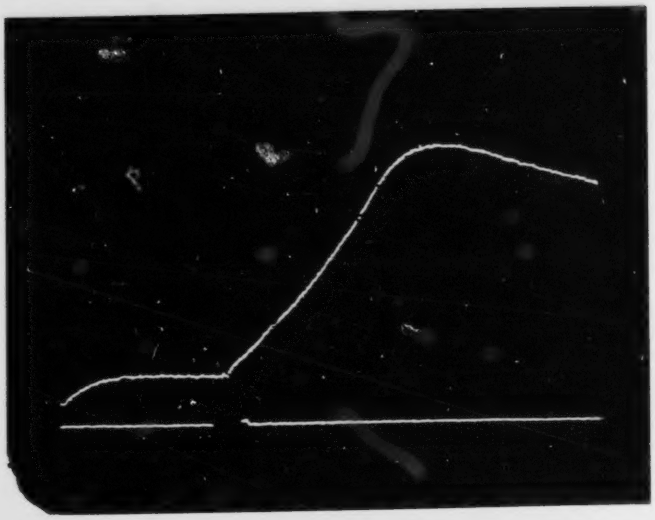


-Dispersion
 Pressure : 200 psig
-Electric Match 1.2g
 Black Powder
-Po : 1 atm
-Time Scale: 0.2
 (sec/div)
-Pressure Scale: 10
 (psi/div)
-Concentration: 90
 (g/m3)
-(dp)comb : 1.949
 (psi)
-(dp/dt)max : 14.620
 (psi/sec)

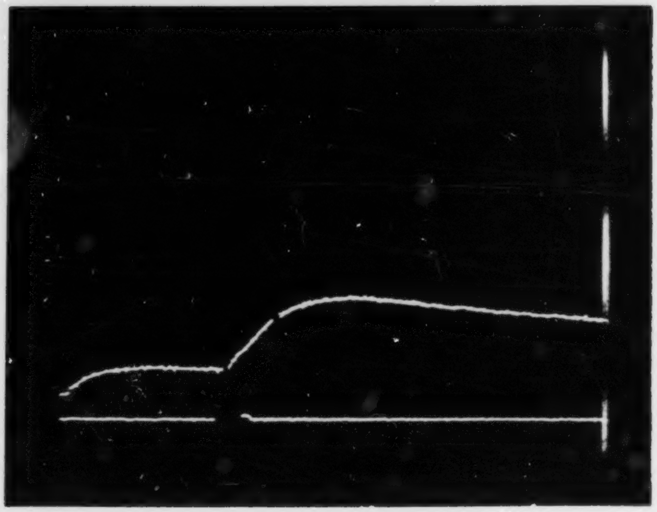


Cornstarch
Time Delay : 600 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 95
(g/m3)
-(dp)comb : 8.187
(psi)
-(dp/dt)max : 14.620
(psi/sec)

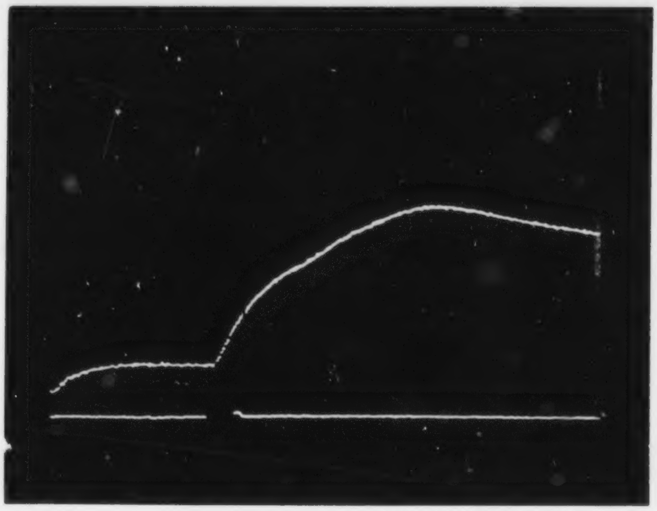


-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 95
(g/m3)
-(dp)comb : 2.534
(psi)
-(dp/dt)max : 10.965
(psi/sec)



Cornstarch
Time Delay : 600 miliseconds

-Dispersion
Pressure : 200 psig
-Electric Match 1.2g
Black Powder
-Po : 1 atm
-Time Scale: 0.2
(sec/div)
-Pressure Scale: 10
(psi/div)
-Concentration: 100
(g/m3)
-(dp)comb : 5.848
(psi)
-(dp/dt)max : 16.244
(psi/sec)



PART II

PROPAGATION AND QUENCHING OF DUST-AIR FLAMES IN A VERTICAL FLAME TUBE

by

R. Knystautas
J.H. Lee
A. Makris

McGill University,
Montreal, Quebec

May 1988

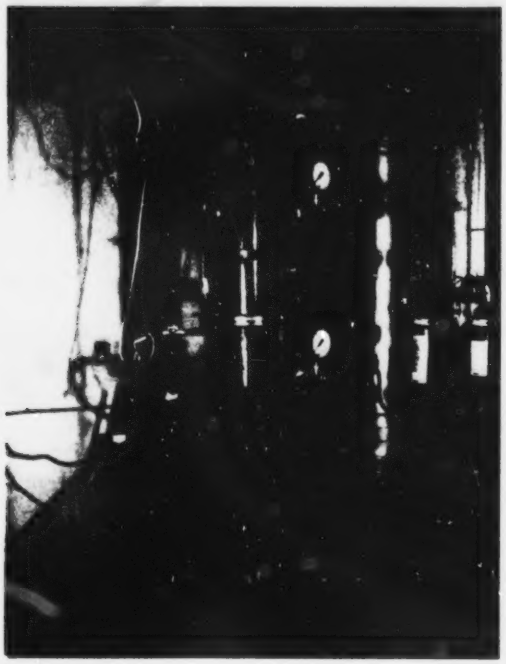
1. INTRODUCTION

Most studies of dust explosions in the past three decades have made use of the confined volume Hartmann-type of explosion vessel. This type of experiment unfortunately limits the study to the measurement of global type of quantities related to the pressure-time history in the explosion vessel. Typical quantities that can be deduced from such experiments are flammability and ignitability requirements as well as the maximum overpressure achieved and the burning rate or the K_{ST} factor. Since the propagation of the flame "front" in a dust-air mixture under such conditions usually cannot be easily observed, the important fundamental dust combustion properties, which are usually related to the flame front propagation, cannot be determined.

In the past several years, largely as a result of EMR sponsorship, we have developed a modular dust combustion tube which by stacking vertically up to four individual self-contained units ($\sim 1\ m$ long each) can produce a vertical dust combustion tube up to about $4\ m$ long. This permits dust flame propagation to be studied either in the upward or downward propagation mode. Moreover, the tube can be operated closed or open to simulate constant volume or constant pressure conditions. Arrays of quenching gaps can also be inserted between sections to study flame propagation and quenching through the gaps. This apparatus has already been used in experiments to measure the flammability limits and quenching distance at constant pressure for a number of dusts. The results were reported at the 21st International Combustion Symposium, Munich and the reprint is appended to this report as Appendix I. For the current work, ignition, propagation, flammability and quenching experiments were carried out for the two Canadian coal dust samples supplied by EMR.

2. EXPERIMENTAL DETAILS

For the purposes of the present experiment, two modular sections of the vertical combustion tube were used. The total length of the tube is 1.820 *m* and the inner diameter is 0.190 *m*. The apparatus is shown in the photograph below and schematically in Fig. 1. The ends of the tube are initially closed by blind flanges. The method of dust dispersion is essentially a linear version of the circular perforated tube used by Bartknecht in his standard 20 litre sphere or the 1 m^3 vessel. The linear dispersion tube in the present apparatus is 14 *mm* in diameter and 910 *mm* long running along one side of the inner wall of the explosion tube. Holes of diameter ranging from from 1 *mm* to 2 *mm* were drilled along the entire length of the dispersion tube. The dispersion tube is connected to a small dust chamber (10 cm^3 volume) then via a solenoid valve to a high pressure air reservoir (230 cm^3 capacity). The air reservoir is pressurized to an overpressure ranging from 10 to 25 *bars*. When the solenoid valve is activated, the dust is convected along with the air flow and the dust-air mixture is discharged into the explosion tube through the linear array of holes. To suppress the directed momentum of the dispersion jets, a circular rod 0.95 *cm* diameter is placed 4 *mm* away from the holes running parallel along the length of the dispersion tube. The rod provides an obstacle to break the jet momentum,



PHOTOGRAPH OF THE VERTICAL DUST COMBUSTION TUBE preventing the dust-air jet from impacting on the opposite wall. Also, a deflected linear jet entrains and disperses more effectively resulting in a more uniform distribution of dust inside the explosion tube. To further optimize the dispersion process, the dust container is placed at the top so that the dust-air would flow downward along the dispersion tube to be discharged into the explosion vessel. To permit a more even dust distribution along the length of the tube, the diameter of the dispersion holes in the middle have been slightly enlarged compared to that at the ends.

A grid of steel quenching plates is held in the middle of the test apparatus between the two sections. For constant pressure experiments the top cover flange has a 28.6 *mm* orifice. The orifice is used to damp vibrations while allowing the flame to propagate toward what is effectively a closed end. The flange on the bottom end of the tube holds the igniter. It is free-floating so that it can either close or open the bottom of the tube.

Before an experiment the vessel is first evacuated to 150 *torr* below atmospheric pressure. The experiment begins with the opening of a solenoid valve causing the dispersion of the dust by an air blast from a 0.23 *L* compressed air reservoir. The air passes through the dust reservoir where it entrains the dust which is then dispersed by the perforated tube located inside the test vessel. The duration of the dispersion process is less than 100 *ms* and the mixture introduced causes the pressure to increase. Ignition with a 1.2 *gram* black powder match with a calorimetric energy of 12 *J* follows the beginning of dispersion by 200 *msec*. The pressure at ignition is slightly less than 0.1 *MPa* absolute. The increasing pressure releases the cap at the top end of the tube and the cover-flange at the bottom end of the tube. Once the tube is open the pressure remains constant, the combustion products vent to the atmosphere and the flame propagates upward freely. After each test the dispersion system is purged of any residue and the tube is opened and swept clean.

The time delay between dispersion and ignition is controlled by a electronic time delay generator. Two limit switches control the opening and closing of the solenoid valves, and one limit switch controls the time of ignition. The flame arrival is detected at the axis of the test vessel by four ionization probes biased at a 700 *VDC* potential and their signals are recorded on an oscilloscope. The quenching distance of the flame is measured by varying the composition of the fuel-air mixture until the limit concentration is found for a particular gap. The quenching plates measure 1.5 *mm* × 75 *mm* × 130 *mm* and are arranged to form a 130 *mm* square grid with the 75 *mm* edge parallel to the axis of the tube. The quenching distance is adjusted by varying the size of the spacers placed between the quenching plates. The number of plates used varies with the size of the spacers.

The solid fuels used are cornstarch and the coal dusts. The mean dust-air mixture composition is varied by changing the mass of dust placed in the dispersion vessel. Distribution of dust along and across the tube are controlled during it dispersion by the calibration of the dispersion system. The formation of the dust- air cloud is a transient process – after dispersion the concentration changes along the tube. To ensure that there is dust-air mixture between the quenching plates the initial air pressure of the lower dispersion system is 25–35% greater than that of the upper system. Typical dispersion pressures are 1.03 MPa upper and 1.37 MPa lower (gauge). Upon dispersion, air and dust sweep through the plates as the pressure in the vessel goes to equilibrium. For these conditions high reproducibility of data from experiment to experiment for different concentrations is obtained. The procedure permits a reproducible mixture composition in the region of the quenching plates and makes it possible to properly determine the minimum quenching distance. However the mean concentration at which the minimum quenching distance is determined may not be the absolute concentration – as in other experiments, this quantity may be apparatus dependent. Turbulence due to dispersion is assumed not to affect the flame because its decay time is of the order of 200 ms compared to about 1.0 s required for the flame to reach the quenching plates.

Cornstarch ($C_6H_{10}O_5$) consists mostly of volatiles with little fixed carbon or ash. The particles are nearly spherical in shape and are fairly uniform in size with a mass mean diameter of 15 μm. The method of preparing the cornstarch fuel adopted for the present investigation consists of mixing the cornstarch with 1% by mass of fused silica gel and storing it in an open jar in an oven at $40^{\circ}\ C$. The purpose of the cornstarch dust is to test out the experimental system and procedures and to generate results which can be compared to existing benchmark data. Once the apparatus and procedure have been checked out, tests with the two Canadian coal dusts can be done with confidence. The coal dust used were the Cape Breton sample (325 mesh, $< 44\ \mu m$) and the British Columbia sample of unknown specifications.

3. RESULTS AND DISCUSSION

Since the flame tube can be operated closed or open and has a large value of L/D, one of the first tasks is to determine how to determine whether the dust-air mixture burns (i.e. sustains flame propagation) or not. Clearly, pressure measurement is inappropriate even in the closed condition in view of the large L/D as opposed to a Hartmann-type bomb. The main diagnostic in the dust flame tube consists of ionization probes which detect the passage of the combustion front. In the present experiments four have been installed and their locations are identified in Table 1. Upward direction means that the igniter is at the bottom end and flame propagation is upward. The opposite is true for the downward direction. The criterion for inflammation is obviously when the dust-air flame propagates along the tube and triggers the ionization probes. A mixture is taken to burn when the flame has managed to propagate at least three quarters of the length of the tube, which is when it roughly reaches the third ionization probe.

To assess the effectiveness of the apparatus, cornstarch dust was first used as a test material. A series of experiments were carried out with cornstarch dust-air mixtures in the vertical flame tube under constant pressure conditions. Different dust concentrations were tried (Table 2) at different time delays between ignition and dispersion (Table 3). The leanest dust concentration which could sustain flame propagation for at least three quarters of the length of the flame tube corresponds to 400 gm/m^3 (Table 3). This is in very good agreement with our earlier study by Jarosinski et al (appended here as Appendix I) in which a value of 380 gm/m^3 was quoted as the flammability limit for cornstarch under constant pressure. The discrepancy can be attributed to the slightly different calculated tube volumes, viz. 53.3 *litres* in the Jarosinski et al paper whereas we have taken the more accurately measured value of 51.7 *litres* in the present experiments. The optimum time delay between dispersion and ignition appears to be $100 - 150$ *msec* which corresponds approximately to the decay time of the dispersion turbulence.

The ignition of the two Canadian coal dusts was then tried under constant pressure conditions in the vertical flame tube. No sustained flame propagation in either of the coal dusts could be achieved regardless of the concentration tried. In retrospect this is not a surprising result because we had observed in our earlier study with Devco 26 coal dust (200 mesh, $< 74\ \mu m$) that no ignition could be achieved either. This implies that the quenching distance for the Devco 26 coal dust is greater than the transverse dimension of our flame tube ($d = 190\ mm$). In Part I of the present report we observed that the flammability limit at constant volume of the Cape Breton coal dust is comparable to that of Devco 26 and that the British Columbia coal dust is much less flammable than Devco 26. This would suggest that both of these coal dusts most likely have quenching distances which are larger than 190 *mm*.

Although ignition at constant pressure of the coal dust could not be achieved for the two samples of Canadian coal supplied to us, it was nevertheless of interest to observe the propagation of flames in these dust-air mixtures. To this end, the two end flanges of our flame tube were bolted shut and dust flame ignition was attempted under this type of "constant volume" condition for upward as well as downward propagation. Again as a reference dust, cornstarch dust was tried first under these conditions. Figs. 2 to 5 show the trajectories of flame propagation under such "constant volume" conditions, for upward and downward propagation, for cornstarch and for the Cape Breton coal dust. No ignition of the British Columbia coal dust could be achieved in the vertical flame tube even under such "constant volume" conditions.

For cornstarch dust (Figs. 2 and 3), the trajectories of the flame indicate first that propagation for the full length of the flame tube could readily be achieved for all but the leanest (75 gm/m^3) dust concentration. Within experimental scatter, there is not too much variation in the flame speed as a function of dust concentration, or rather there does not appear to be any consistent pattern to it. On the average upward flame propagation appears to be marginally more vigorous than downward propagation. This could be possible due to the downward settling of the dust into the upward advancing flame thereby enriching the effective concentration that the flame sees.

The flame trajectories for the Cape Breton coal dust are shown in Figs. 4 and 5 for upward and downward flame propagation. The flames, for other than the leanest concentrations (40 gm/m^3) manage to propagate roughly to half the length of the flame tube under such "constant volume" conditions. There is no doubt that the higher concentrations for this case lead to higher dust flame speeds. Moreover, the upward propagating flames now are clearly more vigorous than downward propagating flames. The difference is much more pronounced for the Cape Breton coal dust than it is for the very flammable cornstarch dust, where the differences are most likely obscured by the relative high flammability of the cornstarch dust.

Figs. 6 to 9 together with Tables 4 to 7 summarize the results for the $(\Delta p)_{max}$, $(dp/dt)_{max}$ and flame speeds achieved for the cornstarch and Cape Breton coal dust achieved under "constant volume" conditions in the vertical flame tube for upward and downward propagation. First, it is to be noted that very lean dust-air flames could be ignited in the vertical flame tube at constant volume as opposed to the 180 litre Hartmann vessel if the 3 *psig* (20.7 MPa) criterion is used to assess flammability. For the cornstarch dust, a lean concentration of 50 gm/m^3 could be ignited while for the Cape Breton coal dust the lean concentration limit is as low as 15 gm/m^3. However, the 20.7 $\overset{k}{\cancel{M}}Pa$ overpressure criterion is not really meaningful for the vertical flame tube with a high L/D ratio. It is important, therefore, to recall that for the coal dust, the flame did not propagate the full length of the tube. The maximum pressure rise for the Cape Breton coal dust rises slowly with concentration and stays at a low level reflecting of course that only a part of the dispersed dust was burned (half the tube length) as contrasted with the cornstarch dust where the pressure rise is steep and the maximum level is much higher. The maximum overpressure again indicates that the upward propagation for both cornstarch and coal dust is more effective.

4. CONCLUSIONS

A series of experiments was carried out in a vertical flame tube to study the flammability and quenching of Canadian coal dust supplied by EMR. To check out the experiment, cornstarch dust was first used. Agreement with previous measurements for the flammability limit under constant pressure was achieved for the cornstarch-air mixture. The Canadian coal dusts could not be ignited to sustain flame propagation in the vertical flame tube under constant pressure conditions. This indicates that the quenching distance for both coal dusts is in excess of 190 *mm*, which is the transverse dimension of the flame tube. Since the Cape Breton coal dust was found to have identical flammability limit at constant volume to the Devco 26 coal dust, which also had a quenching distance in excess of 190 *mm*, the results are not too surprising. The British Columbia coal dust is much less flammable than either the Cape Breton or the Devco 26 coal dusts.

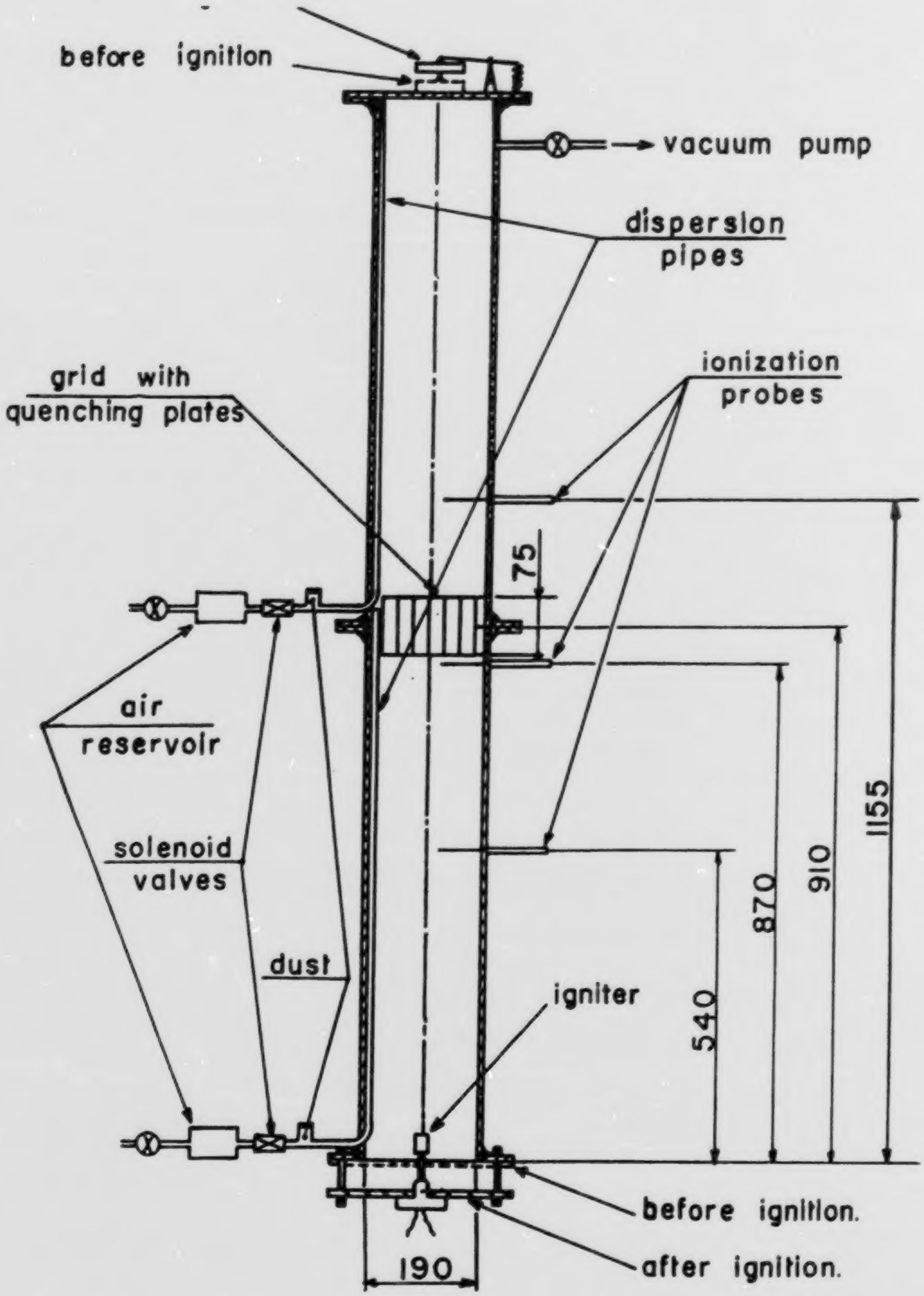

before ignition
vacuum pump
dispersion pipes
ionization probes
grid with quenching plates
75
air reservoir
solenoid valves
dust
igniter
540
870
910
1155
before ignition.
after ignition.
190

FIG · 1

CONSTANT VOLUME UPWARD PROPAGATION IN VERTICAL TUBE

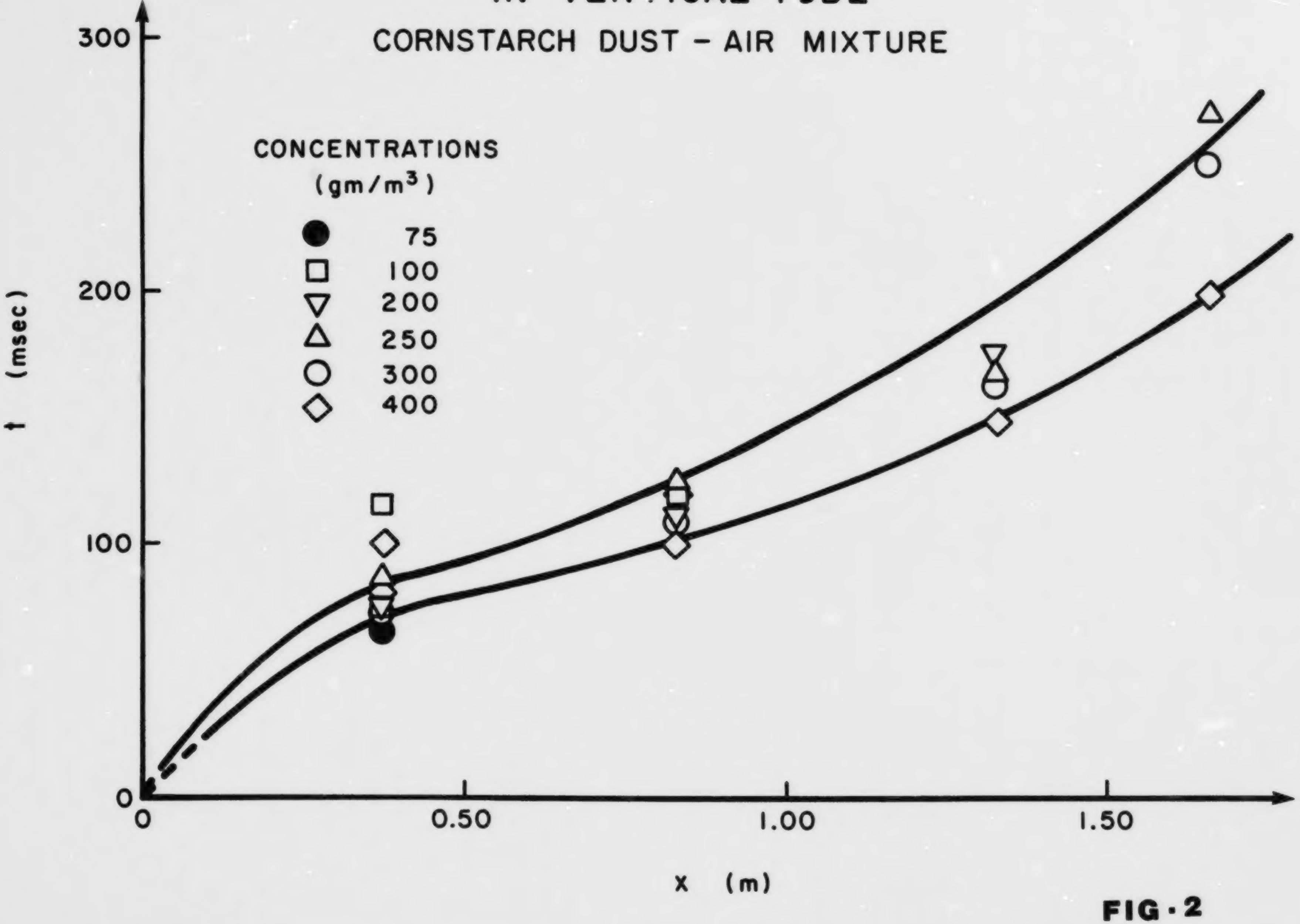


FIG. 2

CONSTANT VOLUME DOWNWARD PROPAGATION IN VERTICAL TUBE

CORNSTARCH DUST - AIR MIXTURE

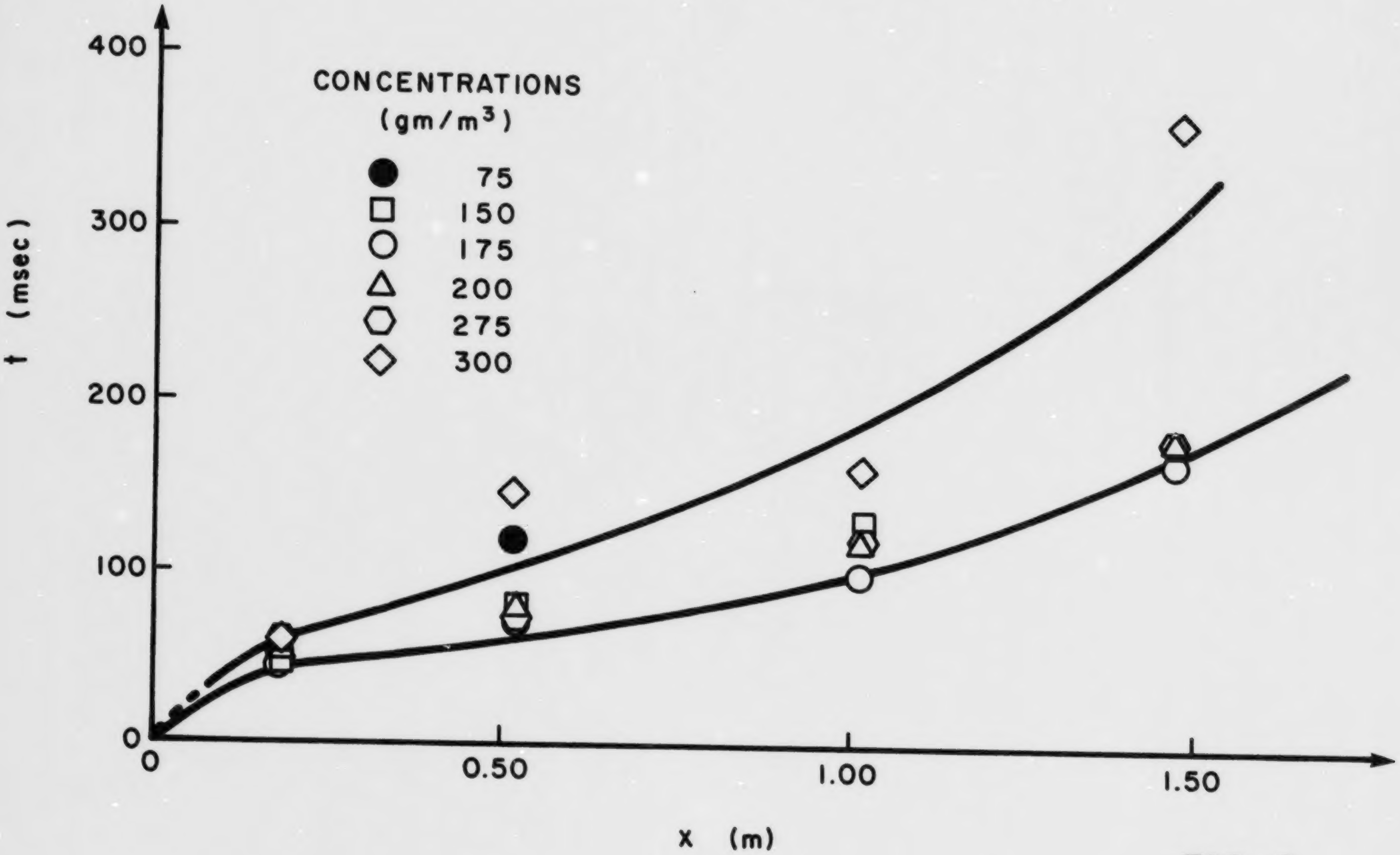
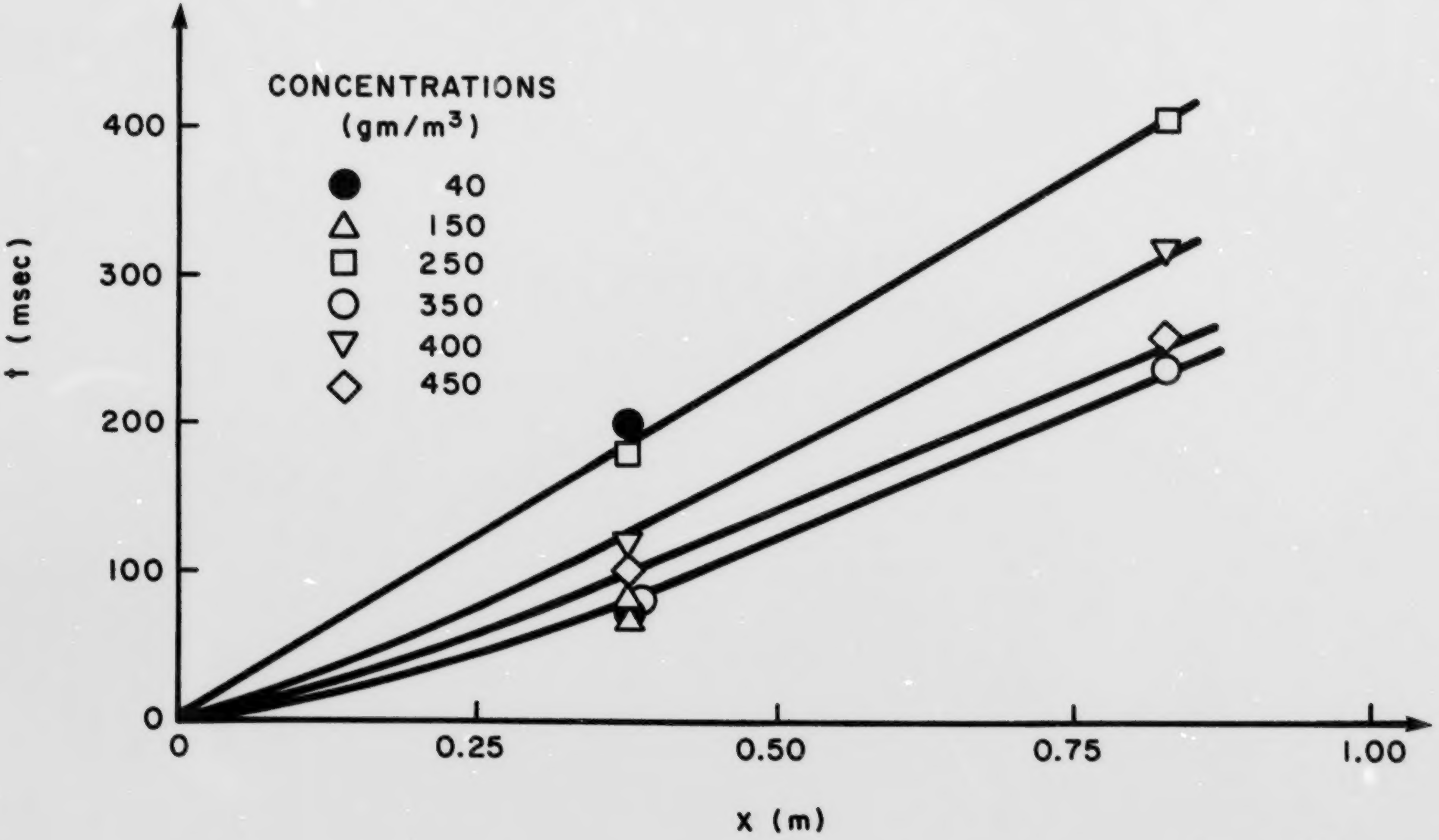


FIG · 3

CONSTANT VOLUME UPWARD PROPAGATION
IN VERTICAL TUBE

COAL DUST (C.B.) - AIR MIXTURE



FIG·4

CONSTANT VOLUME DOWNWARD PROPAGATION IN VERTICAL TUBE

COAL DUST (C.B.) - AIR MIXTURE

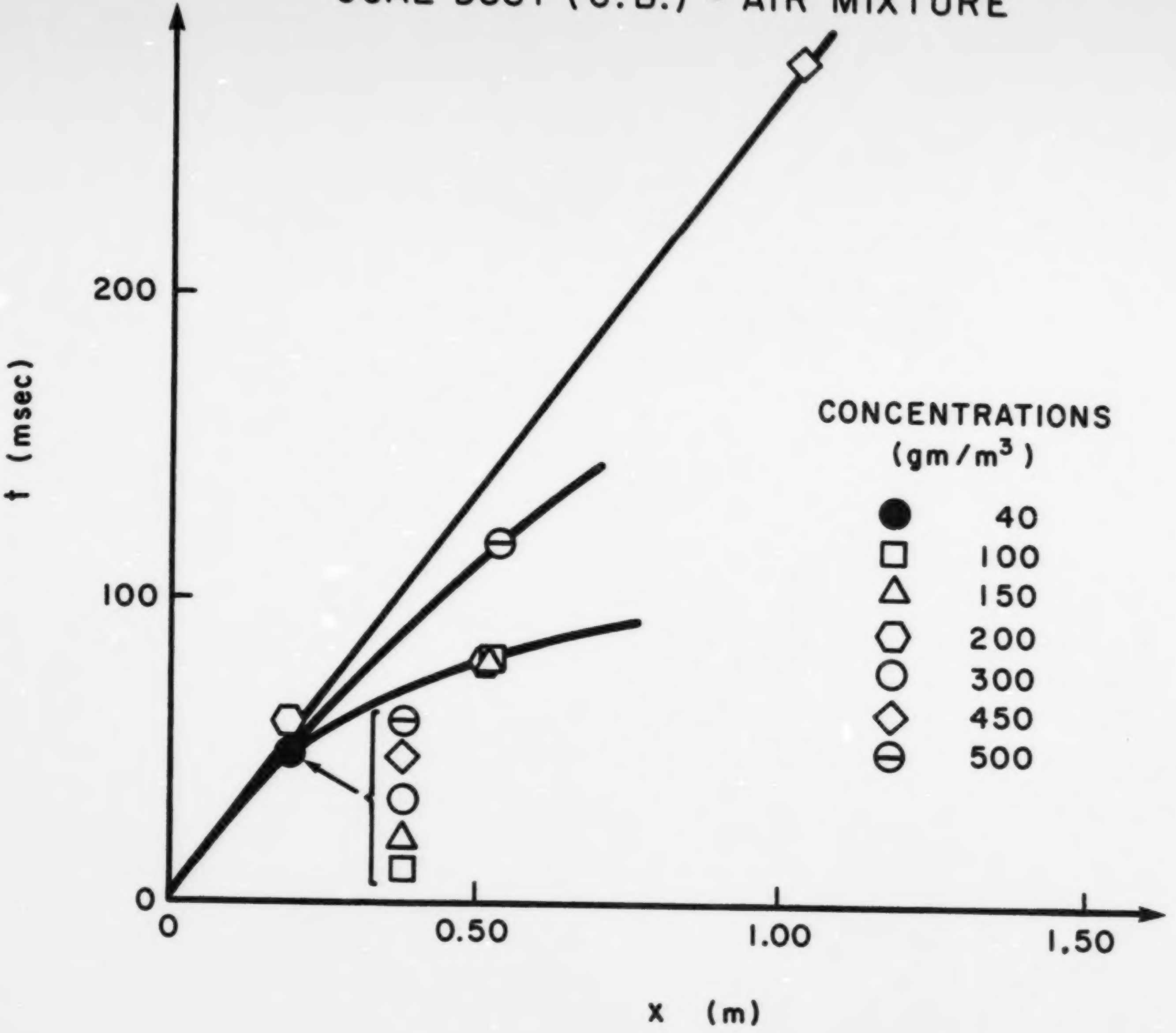
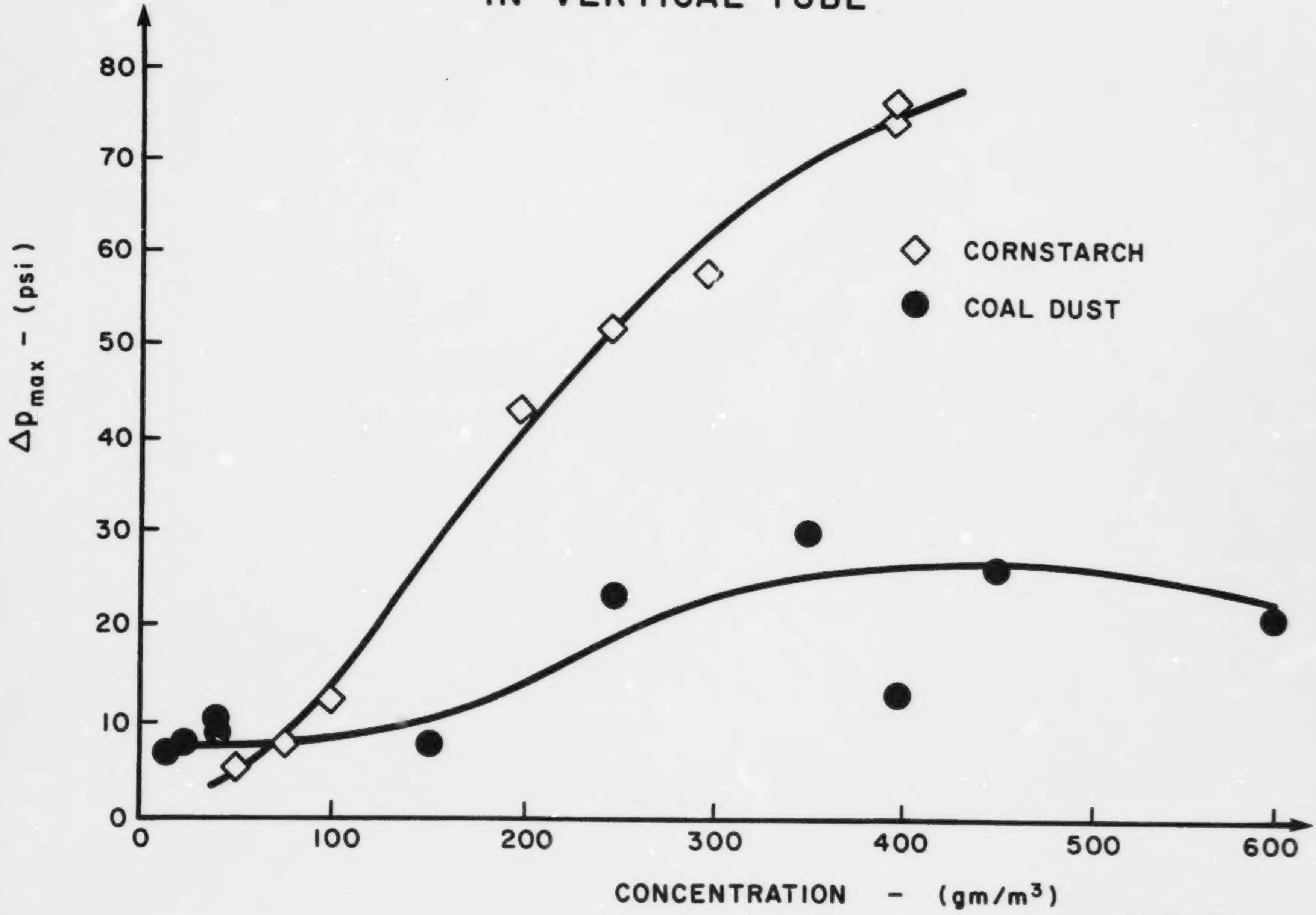


FIG. 5

CONSTANT VOLUME UPWARD PROPAGATION IN VERTICAL TUBE



FIG·6

CONSTANT VOLUME UPWARD PROPAGATION
IN VERTICAL TUBE

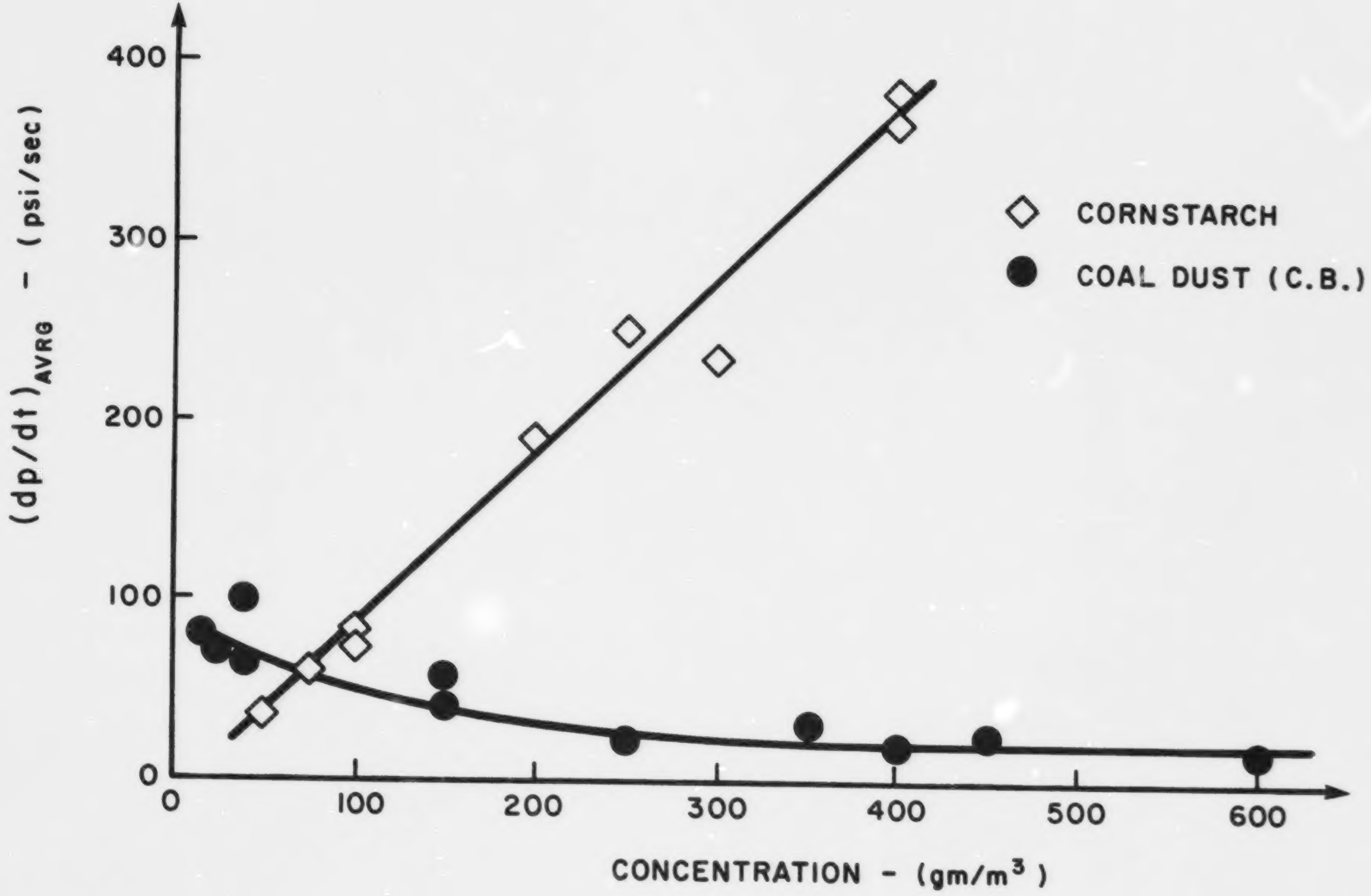
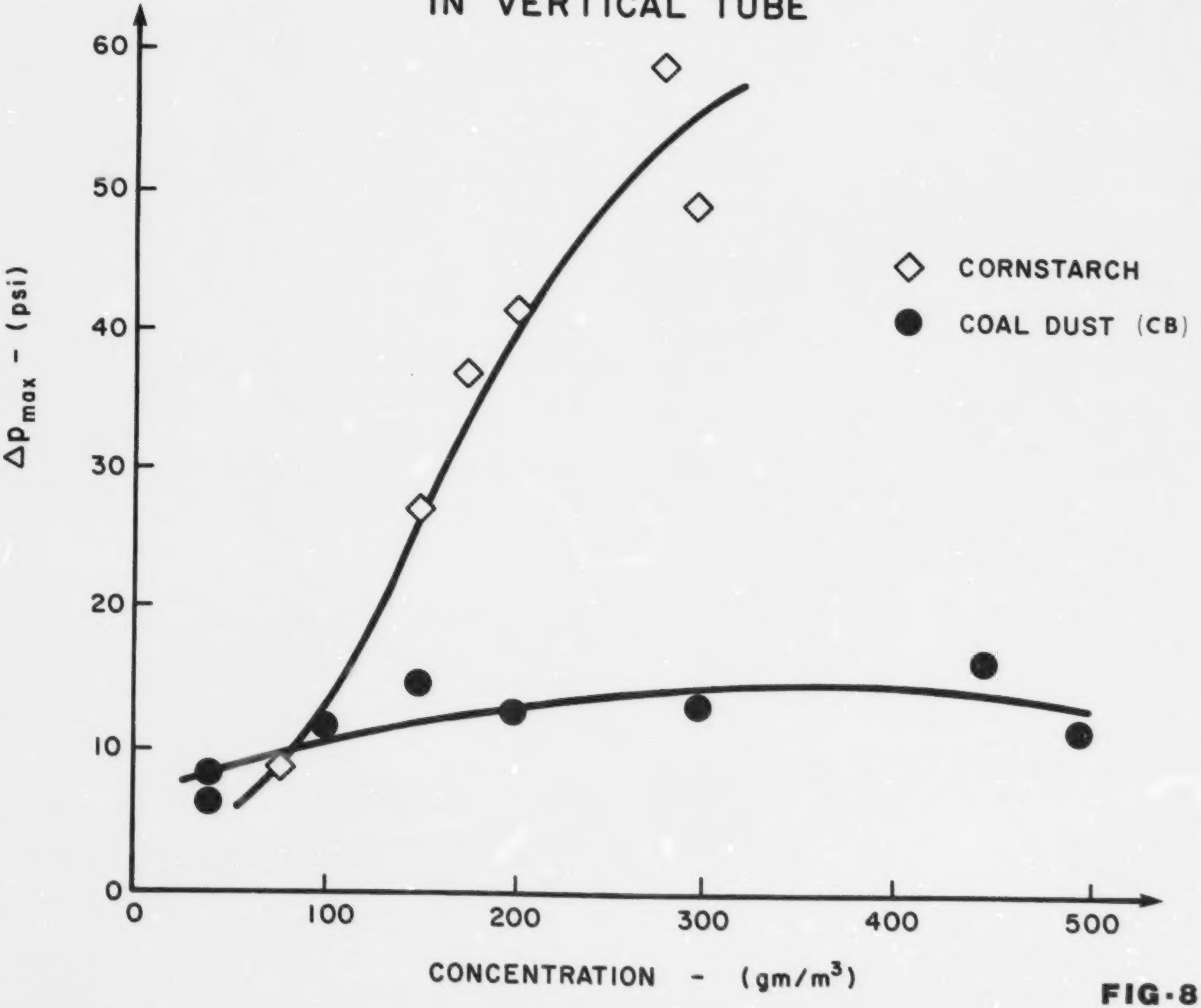


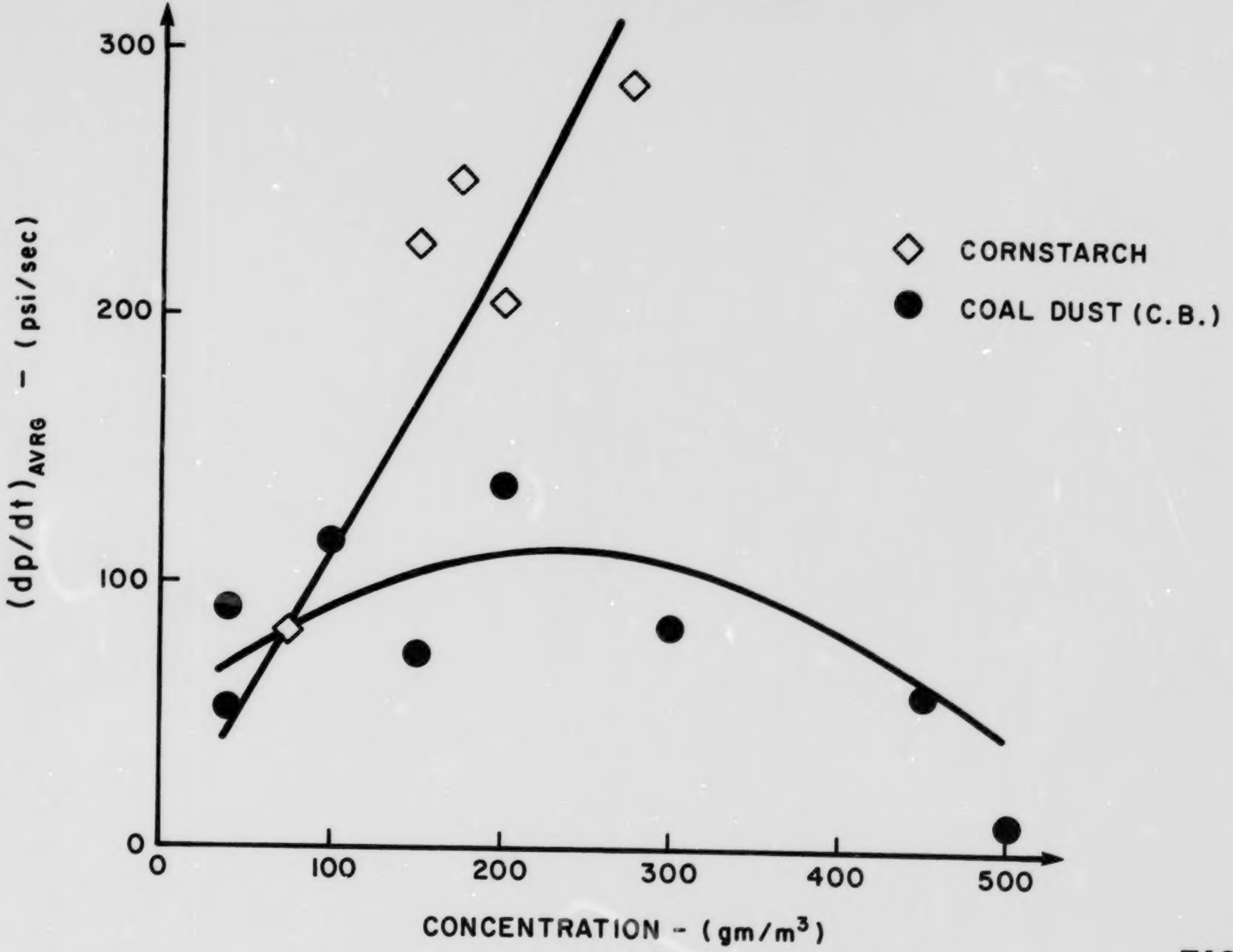
FIG · 7

CONSTANT VOLUME DOWNWARD PROPAGATION IN VERTICAL TUBE



FIG·8

CONSTANT VOLUME DOWNWARD PROPAGATION
IN VERTICAL TUBE



FIG·9

POSITION OF PROBES				
	DISTANCE BETWEEN PROBES (cm)			
	IGNITER TO 1ST PROBE	1ST PROBE TO 2ND PROBE	2ND PROBE TO 3RD PROBE	3RD PROBE TO 4TH PROBE
UPWARD DIRECTION	37.5	45.0	49.5	33.5
DOWNWARD DIRECTION	19.0	33.5	49.5	45.0

TABLE 1

CONSTANT PRESSURE UPWARD PROPAGATION IN VERTICAL TUBE

CORNSTARCH DUST - AIR MIXTURE

CONCENTRATION (gm/m^3)	FLAME SPEED BETWEEN PROBES (m/sec)			
	IGNITER TO 1ST PROBE	1ST PROBE TO 2ND PROBE	2ND PROBE TO 3RD PROBE	3RD PROBE TO 4TH PROBE
350	1.2	0.6	-	-
380	1.1	1.8	-	-
400	1.1 1.3	1.5 1.5	.4	-
430	0.7	1.6	-	-
450	1.3	1.2	-	-
500	1.0	2.0	0.7	-
500	1.1	1.8	1.0	-
550	1.0	1.4	0.8	1.2

TABLE 2

CONSTANT PRESSURE UPWARD PROPAGATION IN VERTICAL TUBE

CORNSTARCH DUST - AIR MIXTURE (400 gm/m^3)

TIME DELAY BETWEEN DISPERSION AND IGNITION (msec)	FLAME SPEED BETWEEN PROBES (m/sec)			
	IGNITER TO 1st PROBE	1st PROBE TO 2nd PROBE	2nd PROBE TO 3rd PROBE	3rd PROBE TO 4th PROBE
60	1.3	1.5	0.4	-
100	1.2 .7	0.5 1.3	1.2 .8	-
150	0.8	2.2	0.8	-
200	1.1	1.6	-	-

TABLE 3

CONSTANT VOLUME UPWARD PROPAGATION IN VERTICAL TUBE

CORNSTARCH DUST - AIR MIXTURE

CONCENTRATION (gm/m^3)	Δp_{max} (psi)	$\left[\frac{dp}{dt}\right]_{AVRG}$ (psi/sec)	FLAME SPEED BETWEEN PROBES (m/sec)			
			IGNITER TO 1st PROBE	1st PROBE TO 2nd PROBE	2nd PROBE TO 3rd PROBE	3rd PROBE TO 4th PROBE
50	5.2	38	–	–	–	–
75	7.9	61	6.0	–	–	–
100	>7	75	4.7	–	–	–
100	12.4	83	3.4	–	–	–
200	43.4	191	5.0	12.8	7.6	–
250	51.7	253	4.2	12.8	11.0	3.4
300	57.9	238	5.0	12.8	9.0	4.0
400	76.4	372	3.8	9.0	10.0	6.6
400	74.4	387	4.7	11.3	19.5	6.6

TABLE 4

CONSTANT VOLUME DOWNWARD PROPAGATION IN VERTICAL TUBE

CORNSTARCH DUST - AIR MIXTURE

CONCENTRATION (gm/m^3)	Δp_{max} (psi)	$\left[\frac{dp}{dt}\right]_{AVRG}$ (psi/sec)	FLAME SPEED BETWEEN PROBES (m/sec)			
			IGNITER TO 1st PROBE	1st PROBE TO 2nd PROBE	2nd PROBE TO 3rd PROBE	3rd PROBE TO 4th PROBE
75	8.5	83	3.8	4.8	-	-
150	26.9	227	4.2	9.6	9.0	-
175	36.5	250	4.2	11.3	19.8	-
200	41.3	205	3.8	11.3	12.4	7.5
275	58.9	287	3.2	22.5	11.0	7.5
300	>47	-	3.2	3.8	33.0	2.2

TABLE 5

CONSTANT VOLUME UPWARD PROPAGATION IN VERTICAL TUBE

COAL DUST (CAPE BRETON) - AIR MIXTURE

CONCENTRATION (gm/m^3)	Δp_{max} (psi)	$\left[\frac{dp}{dt}\right]_{AVRG}$ (psi/sec)	FLAME SPEED BETWEEN PROBES (m/sec)			
			IGNITER TO 1ST PROBE	1ST PROBE TO 2ND PROBE	2ND PROBE TO 3RD PROBE	3RD PROBE TO 4TH PROBE
15	6.5	80	–	–	–	–
25	8.0	70	–	–	–	–
40	8.9	65	1.9	–	–	–
40	10.3	99	5.0	–	–	–
150	8.3	41	5.4	–	–	–
150	8.3	59	4.7	–	–	–
250	23.0	24	2.0	1.9	–	–
350	30.0	34	4.7	2.8	–	–
400	13.0	22	3.0	2.3	–	–
450	26.0	28	3.8	2.8	–	–
600	20.7	19	0.67	0.67	–	–

TABLE 6

CONSTANT VOLUME DOWNWARD PROPAGATION IN VERTICAL TUBE

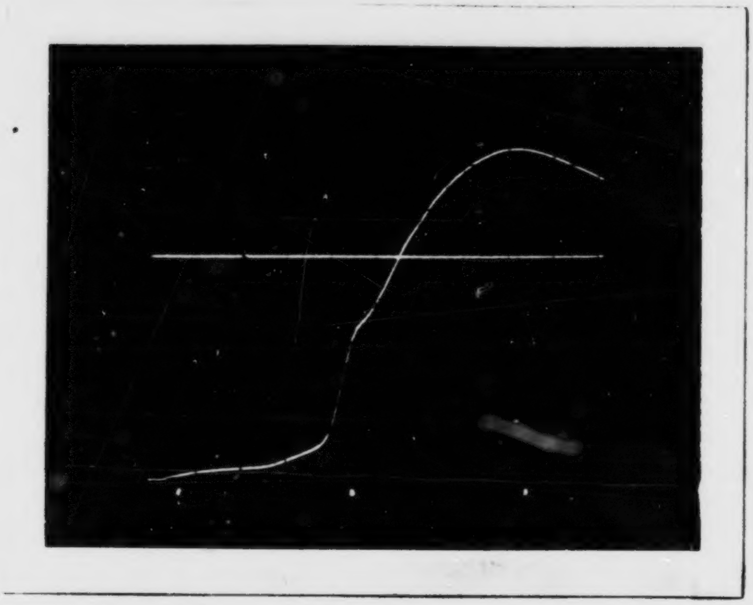
COAL DUST (CAPE BRETON) - AIR MIXTURE

CONCENTRATION (gm/m^3)	Δp_{max} (psi)	$\left[\frac{dp}{dt}\right]_{AVRG}$ (psi/sec)	FLAME SPEED BETWEEN PROBES (m/sec)			
			IGNITER TO 1st PROBE	1st PROBE TO 2nd PROBE	2nd PROBE TO 3rd PROBE	3rd PROBE TO 4th PROBE
40	6.4	53	3.8	-	-	-
40	7.9	90	3.8	-	-	-
100	11.5	115	3.8	11.2	-	-
150	14.5	72	3.8	11.2	-	-
200	12.5	138	3.1	17.0	-	-
300	12.4	82	3.8	-	-	-
450	16.5	68	3.8	-	-	-
500	11.4	12	3.8	4.8	-	-

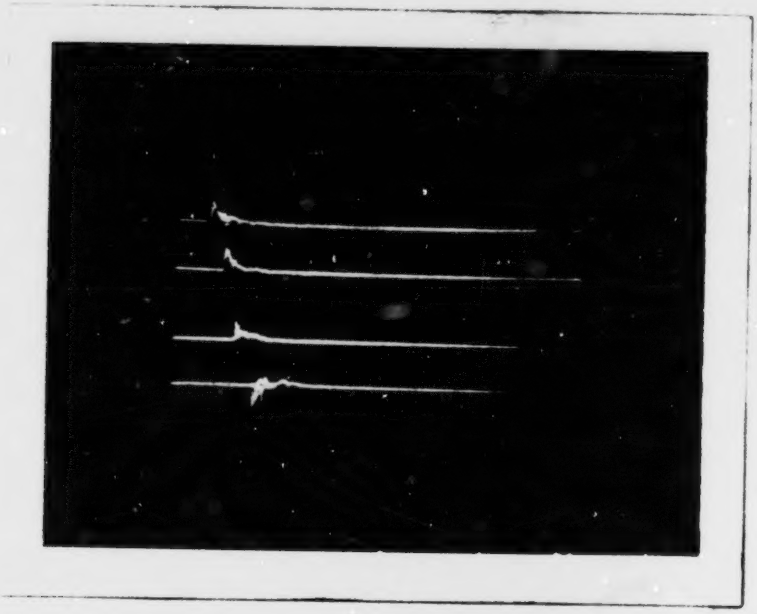
TABLE 7

CONSTANT VOLUME

400 g/m^3 cornstarch
10.4 g/disp
dried for 24 hrs
at 105°C with
1% by mass cab-o-sil



50 ms/div
.1V/div
50mV/div
100ms delay
residual pressure
top: 40 psig
bottom: 0



.1s/div
.1V/div

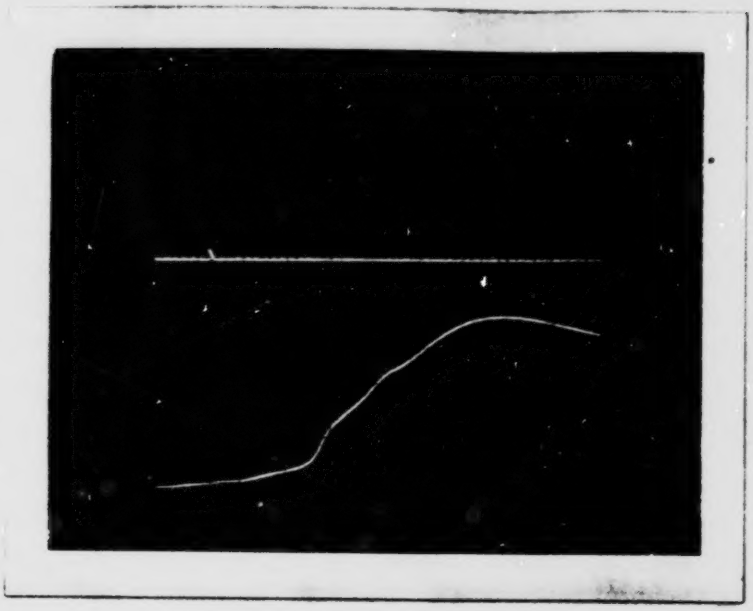
$\Delta p)_{max} = 74.4$ psi

$\overline{\left(\frac{dp}{dt}\right)} = 387$ psi/s

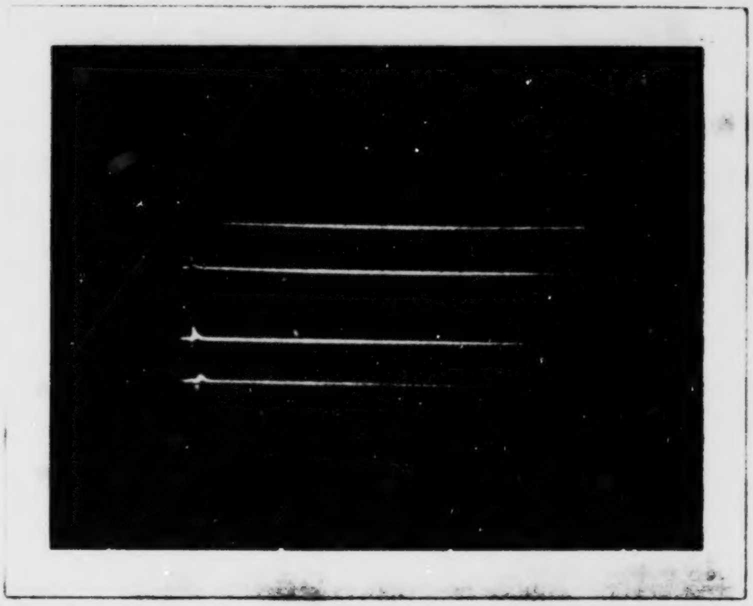
CONSTANT VOLUME

400g/m³ cornstarch
10.4g/disp

cornstarch dried for 24hrs
with 1% by mass cab-o-sil
at 105°C



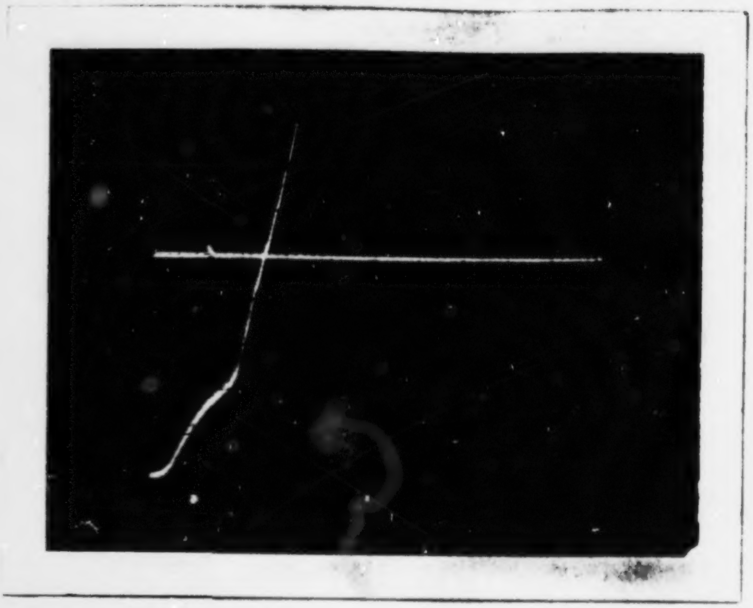
50ms/div
.1V/div
.1V/div
60ms delay
residual pressure
top: 30psig
bottom: 0 psig
$\Delta p)_{max} = 7\overset{4}{6}$ psi

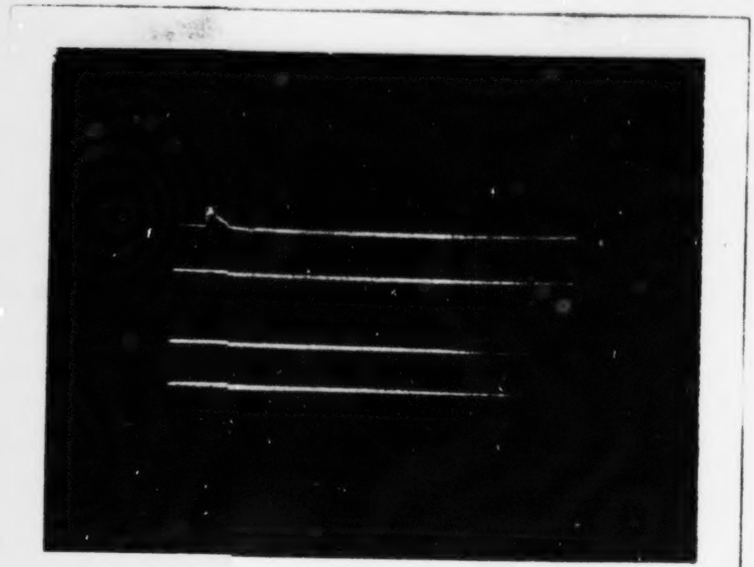


.50s/div
.1V/div

$\left(\frac{dp}{dt}\right) = 372$ psi/s

CONSTANT VOLUME





100g/m³ cornstarch

5.2g/[illegible]

2.6g/disp

24 hrs heated at 105F

1% by mass cab-o-sil

·1V/div

50 ms/div

5mV/div

60ms delay

residual pressure:

top: 10 psig

bottom: 10 psig

$\Delta p)_{max} > 7$ psi

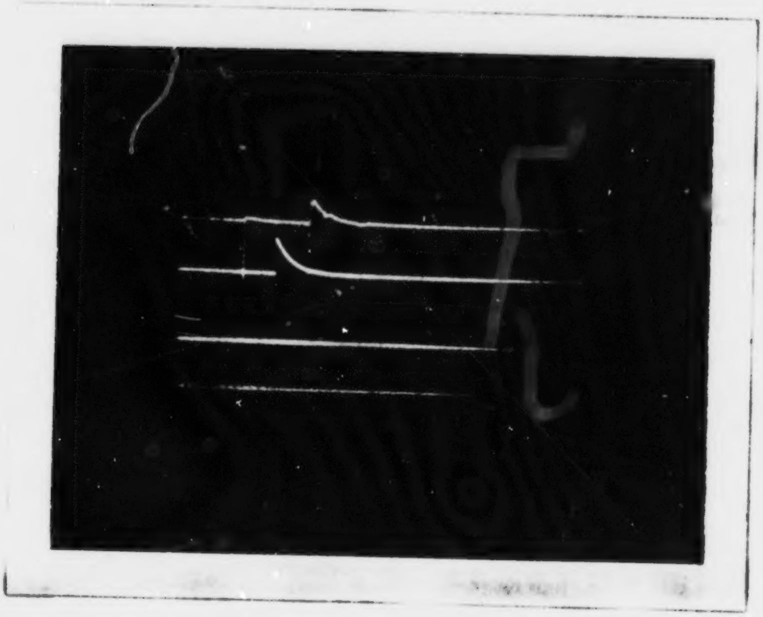
·1s/div

·1V/div

$\left(\frac{dp}{dt}\right) \simeq 75 \frac{psi}{s}$

FOR ALL SUBSEQUENT RESULTS CORNSTARCH USED WAS HEATED FOR 24hrs at 105°C and premixed with 1% by mass cab-o-sil

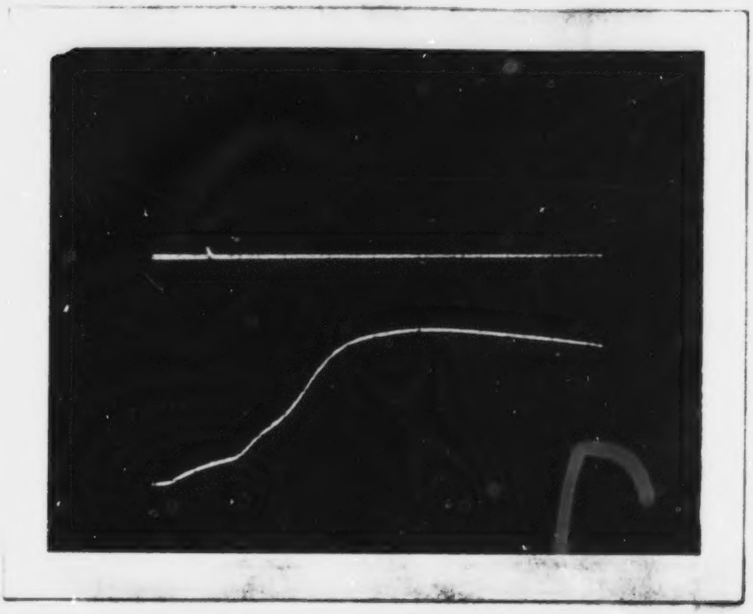
CONSTANT VOLUME



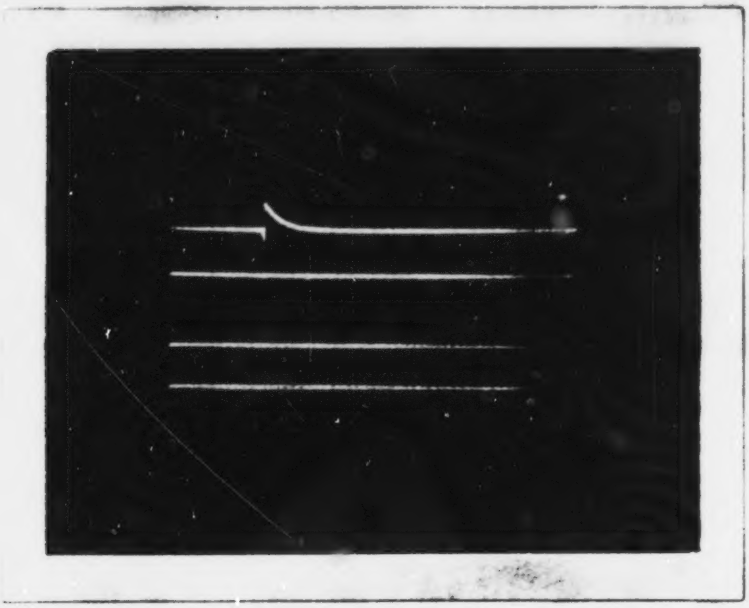
100g/m³ cornstarch
2.6g/disp
50ms/div
.1V/div
60ms delay

pressure trace not recorded ∴ non-memory scope's camera had no film

CONSTANT VOLUME



$100 g/m^3$ cornstarch
2.6g/disp
50ms/div
.1V/div
20mV/div
delay 60ms
residual pressure
top: 14psig
bottom: 14psig
$\Delta p)_{max} \simeq 12.4$ psi
$\left(\frac{dp}{dt}\right) = 83$ psi/s



50ms/div
.1V/div

CONSTANT VOLUME

X

$75\,g/m^3$
cornstarch

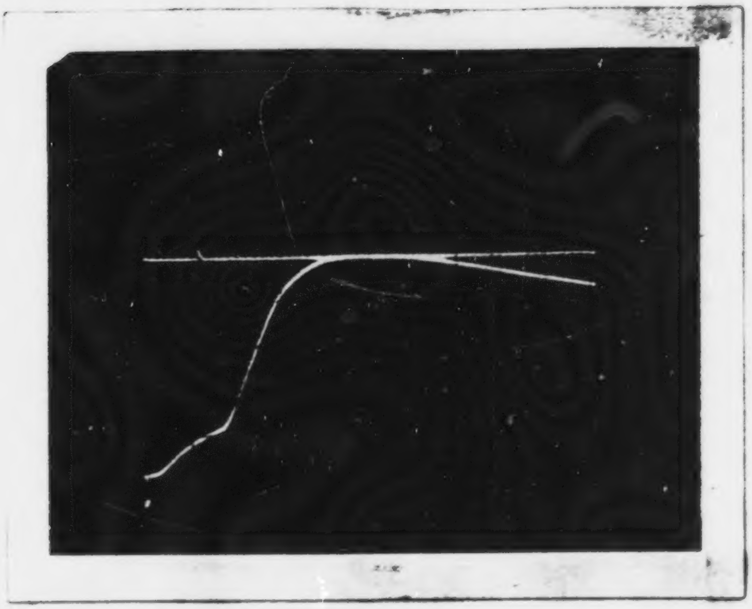
3.9g total
1.95g /disp

50ms/div
.1V/div
10mV/div
60ms delay

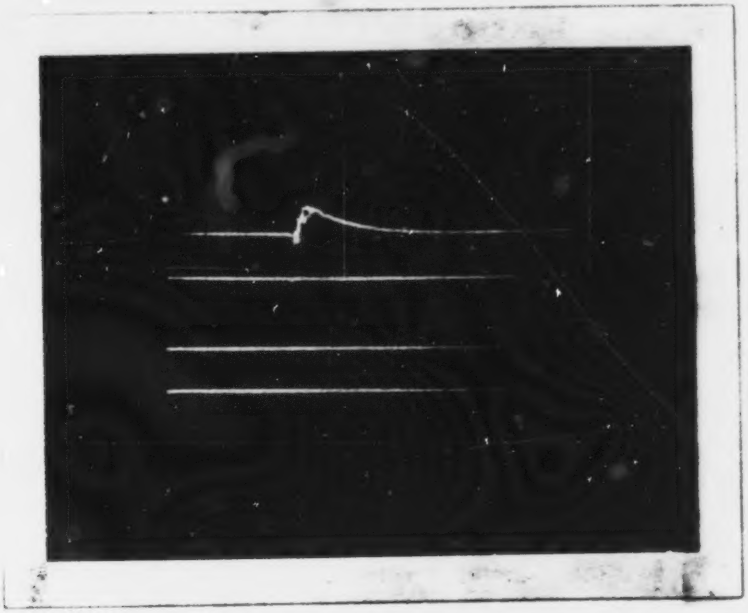
residual pressure
top: 8 psig
bottom: 7 psig

$\Delta p)_{max} = 7.85$ psi

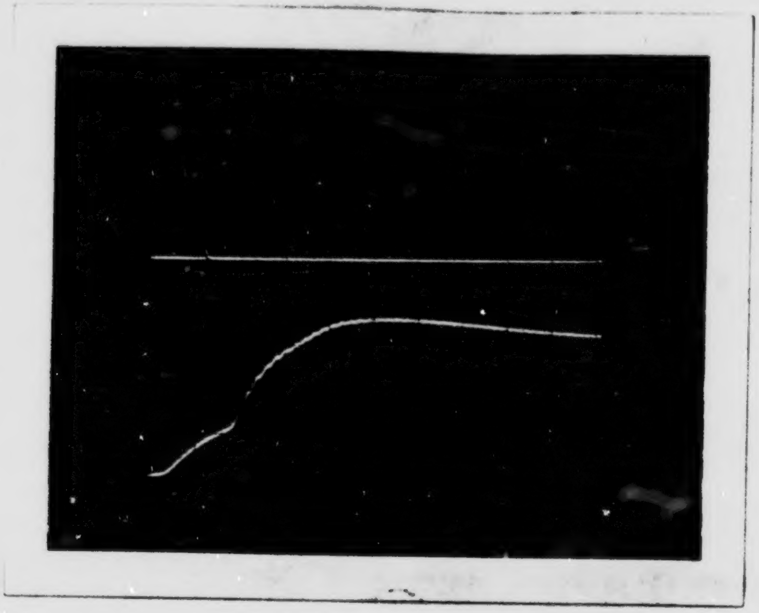
$\left(\frac{dp}{dt}\right) = 61$ psi/s



20ms/div
.1V/div

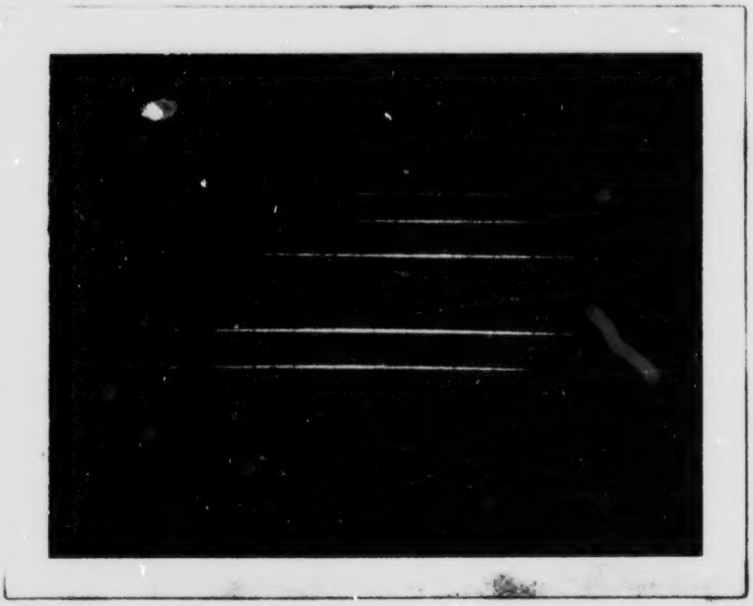


CONSTANT VOLUME



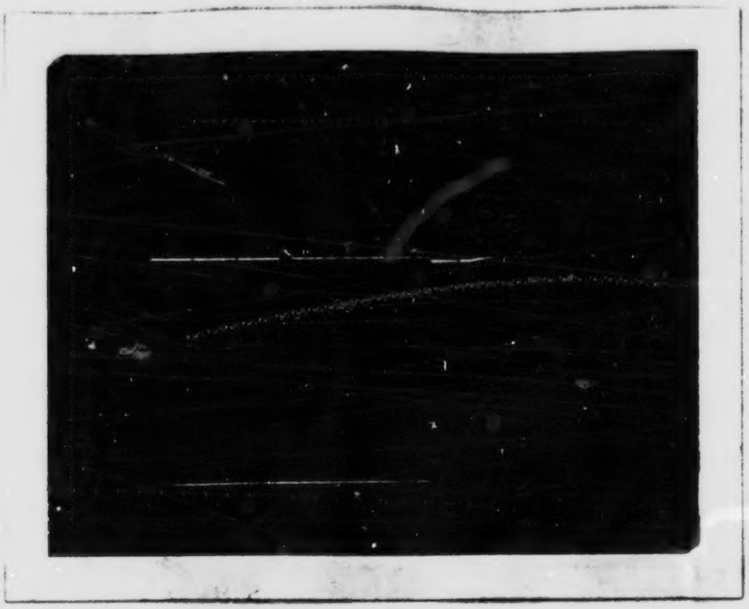
50g/m³
cornstarch
26g total
1.3g/disp
50mV/div
.1V/div
10mV/div
60μs delay
residual pressure
top 6psig
bottom 4psig
$\Delta p_{max} = 5.2 psi$
$\left(\frac{dp}{dt}\right) = 38 \left(\frac{psi}{s}\right)$

20ms/div
.1V/div



CONSTANT PRESSURE

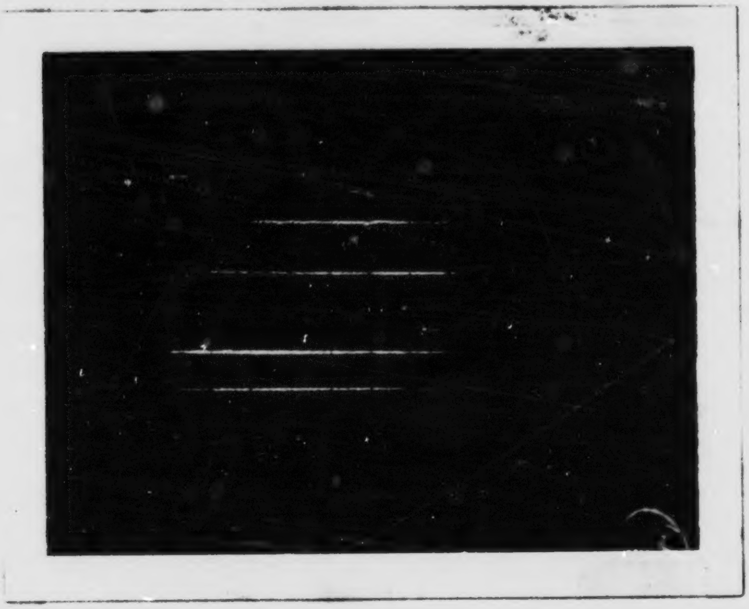
350g/m³ cornstarch
18.2g total
9.1g/disp



20ms/div
.1V/div
.2V/div
60ms delay

No residual pressure

Both wire leads on flanges after separation bend in adverse manner
Γ
L



.2s/div
.1V/div

flame reached last port prior to 2nd ionization probe (after opening tube)

CONSTANT PRESSURE

$380 g/cm^3$ cornstarch

19.76g

⇒ 9.9g/disp

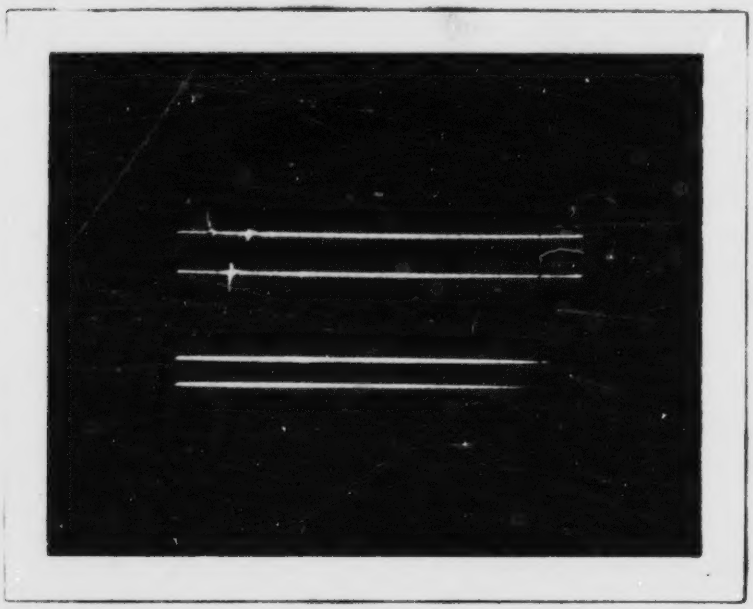
20ms/div

.1V/div

No residual pressure

.5s/div

.1V/div

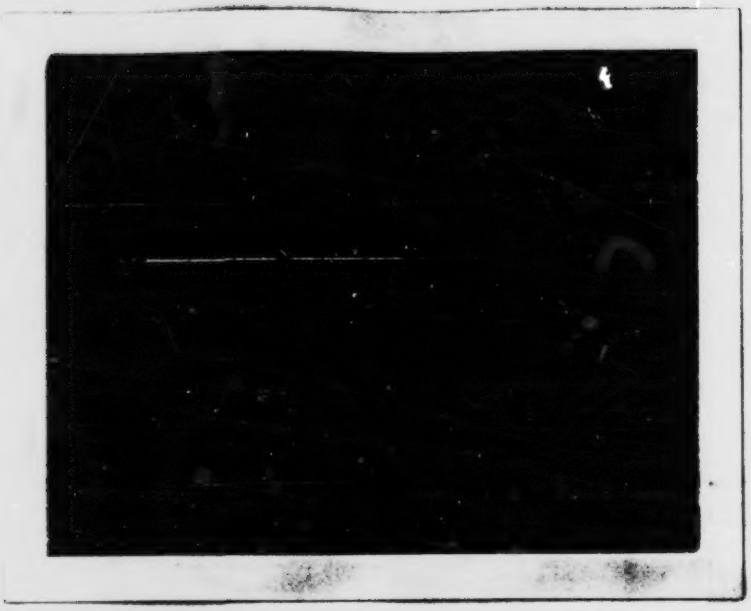


CONSTANT PRESSURE

400g/m³ cornstarch

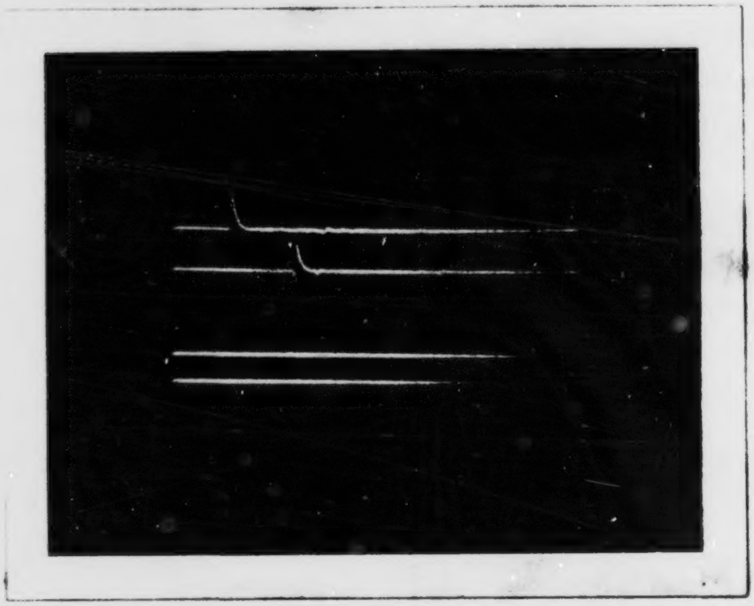
20.8g
→10.4g/disp

20ms/div
.1V/div
60ms delay

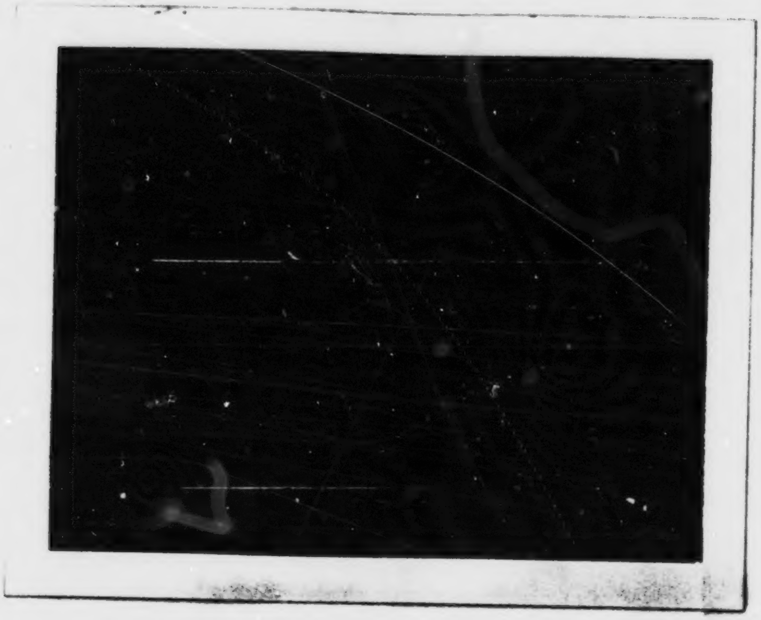


.1V/div
.2s/div

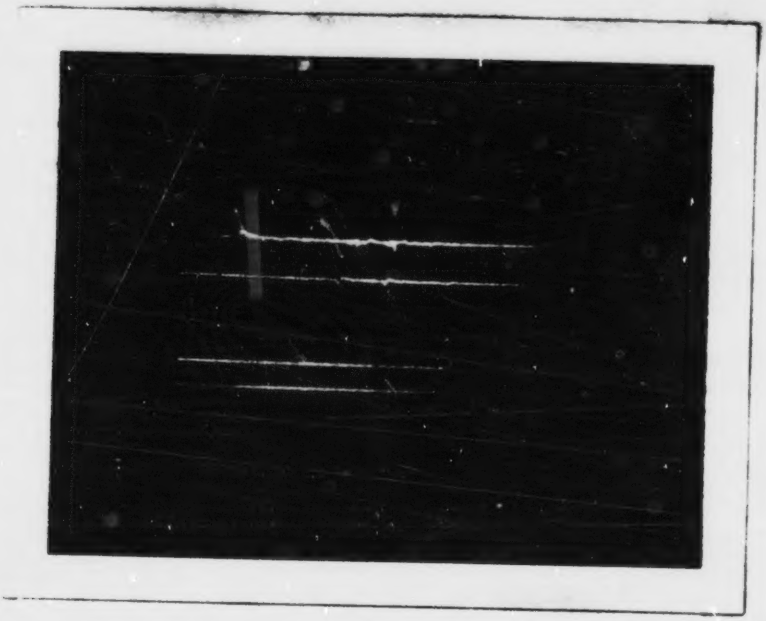
Note: 3rd probe begins to be ionized



CONSTANT PRESSURE



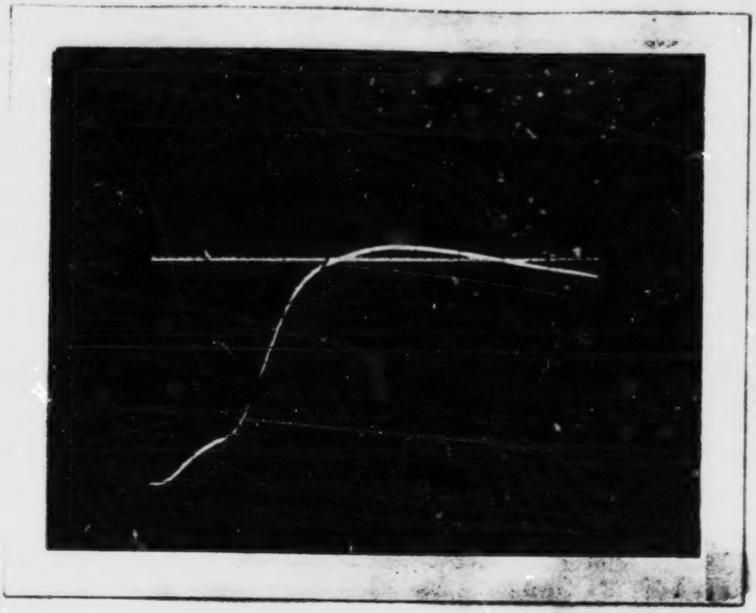
450 g/m^3 cornstarch
23.4g
=>11.7g/disp
.20ms/div
~~50mV/div~~
.1V/div
60ms delay



.2s/div
50mV/div

(leak near
dust placement
chambers)

CONSTANT VOLUME



400g/m³ coal dust C.E.

2.08g ⇒ 1.05/disp

50ms/div

.1V/div

10mV/div

60ms delay

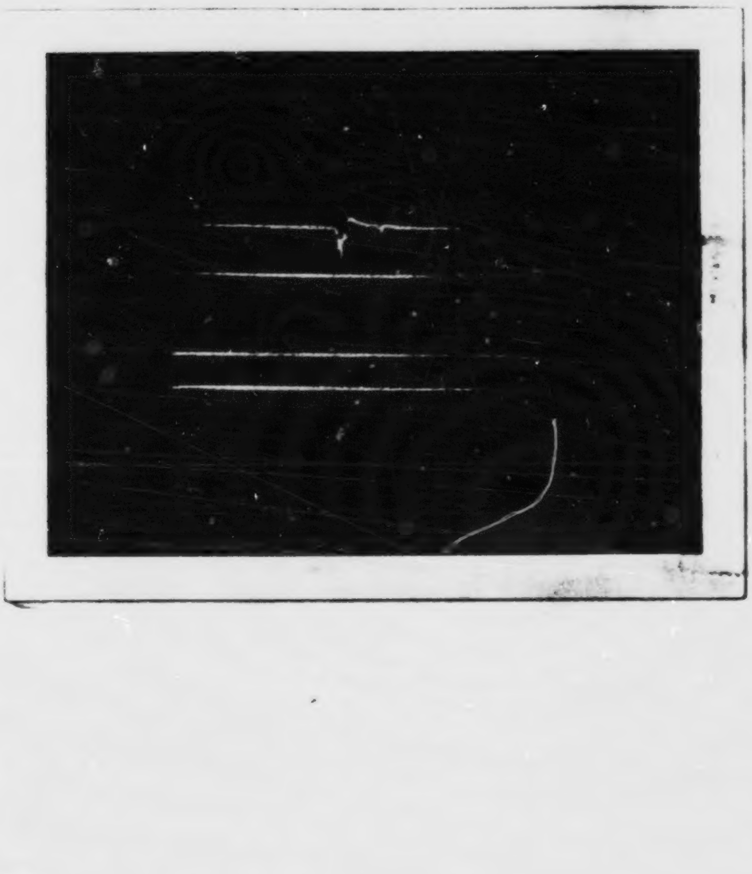
Residual pressure

top: ~10psig

bottom: ~10psig

$\Delta p|_{max} = 8.9$ psi

$\left(\frac{dp}{dt}\right) = 65$ psi/s



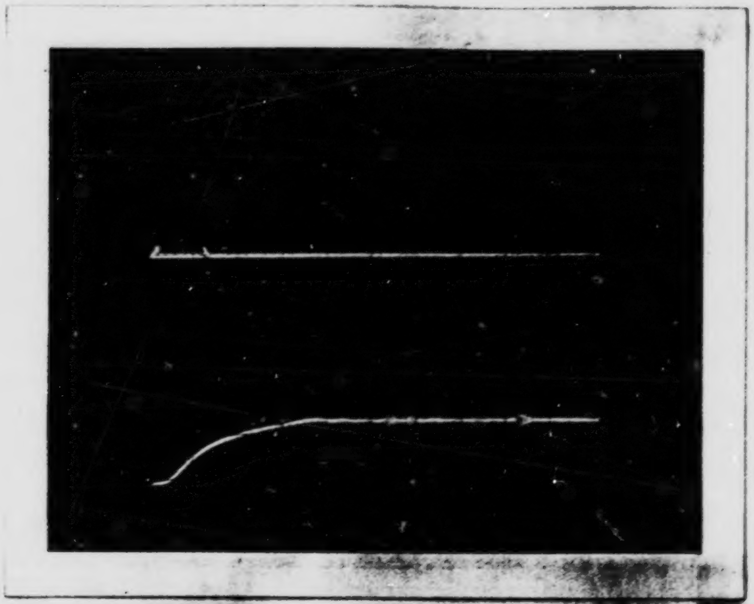
50ms/div

.1V/div

dust prepared for 24 hrs in oven at 105°C

CONSTANT PRESSURE

200g/m³ coaldust C.B.
10.4g → 5.2g/disp



50ms/div
.1V/div
10mV/div
60ms delay

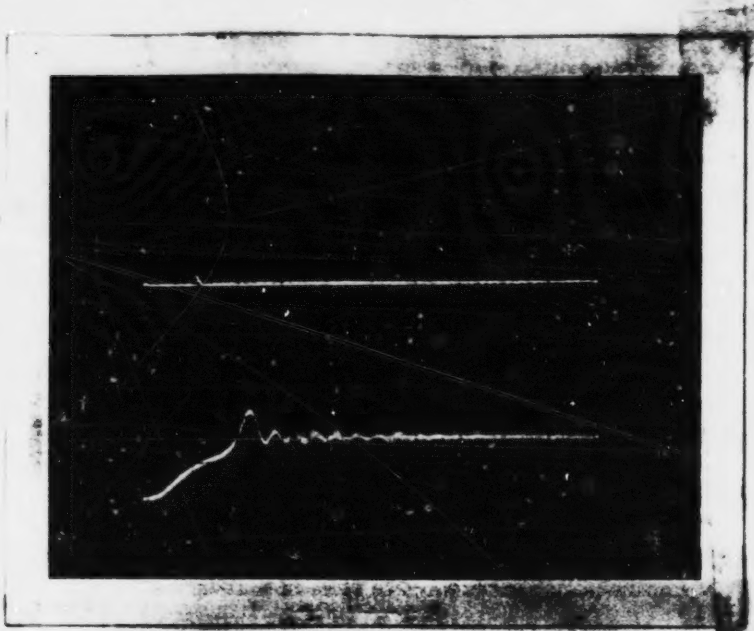
No vibration noises
Dust prepared at
105°C for 24 hrs

.2s/div
.1V/div

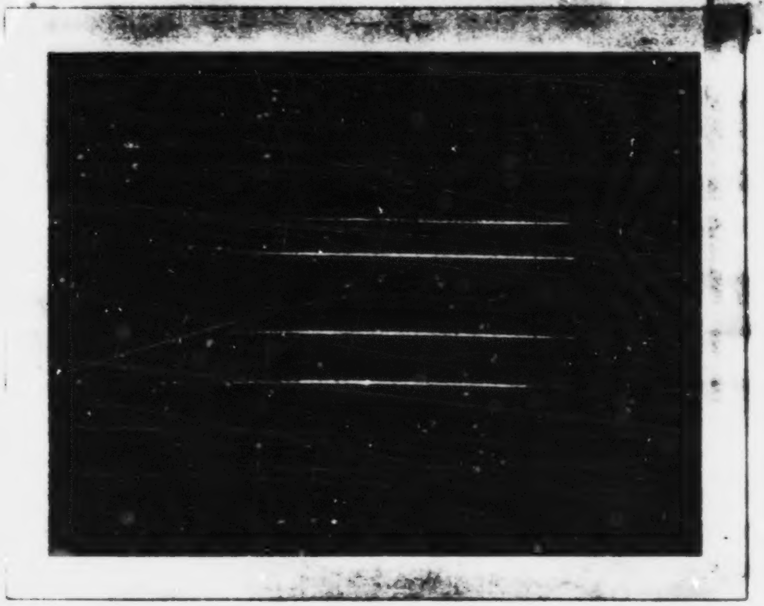
No IGNITION
FAULTY ignitor

CONSTANT PRESSURE

400g/m³ coal dust C.B.
10,4g/disp ~~5.2g/dis~~p
50ms/div
·1V/div
10mV/div
60ms delay
Dust prepared at
105°C, 24hrs



·1V/div
·2s/div

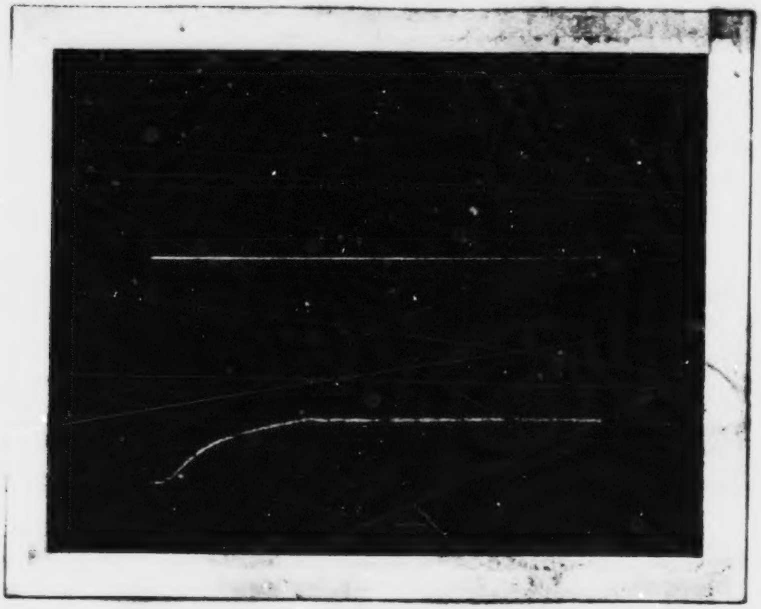


CONSTANT PRESSURE

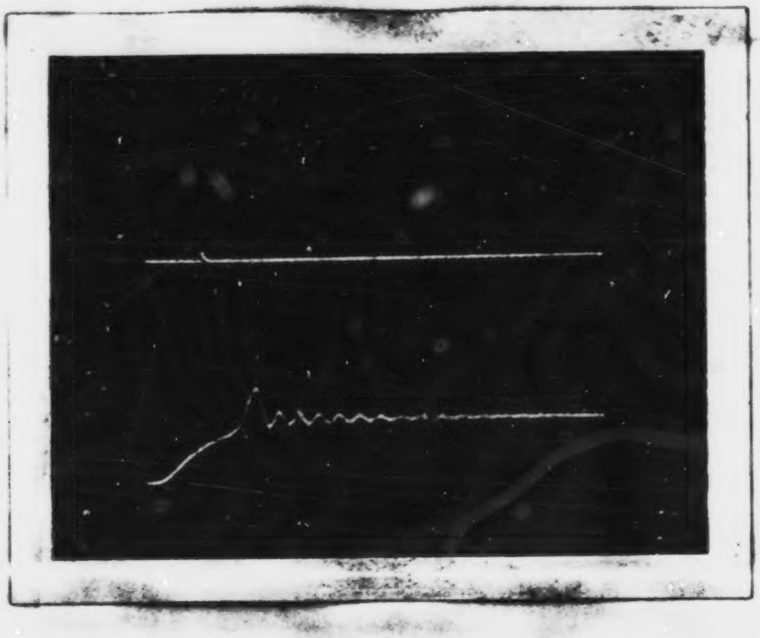
200g/m³ coal dust C.B.

NO IGNITION

fusion wire broke-off



200g/m³ coal dust C.B.



10.4g
5.2g/disp
50ms/div
.1V/div
10mV/div
prepared for 24hrs at 105°C
fusion wire length - 5½"

NO ION PROBE
TRIGERRING
LOCAL BURNING;
VIBRATIONS

CONSTANT PRESSURE 500g/m^3 coaldust C.B.

26g ⇒ 13g/disp

50ms/div

·1V/div

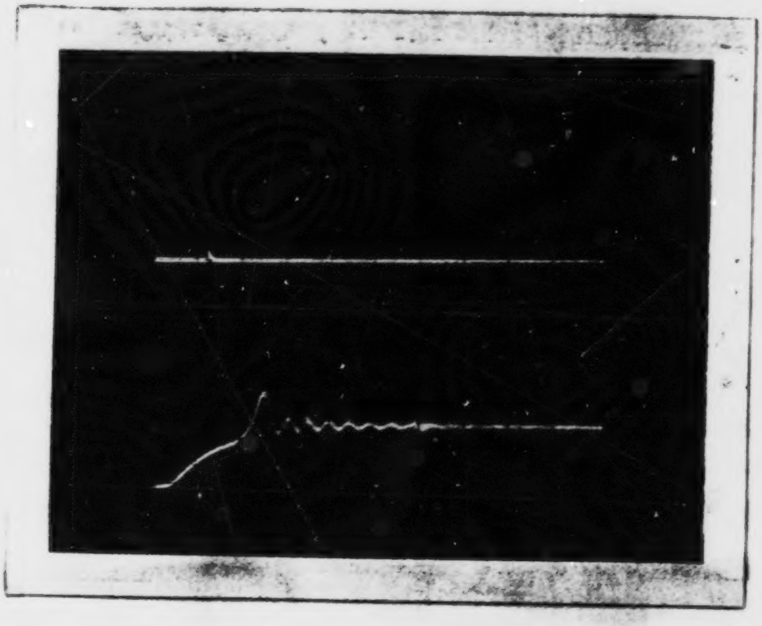
10mV/div

60ms delay

ignition!

20kV - resistors

No IONIZATION OF PROBES

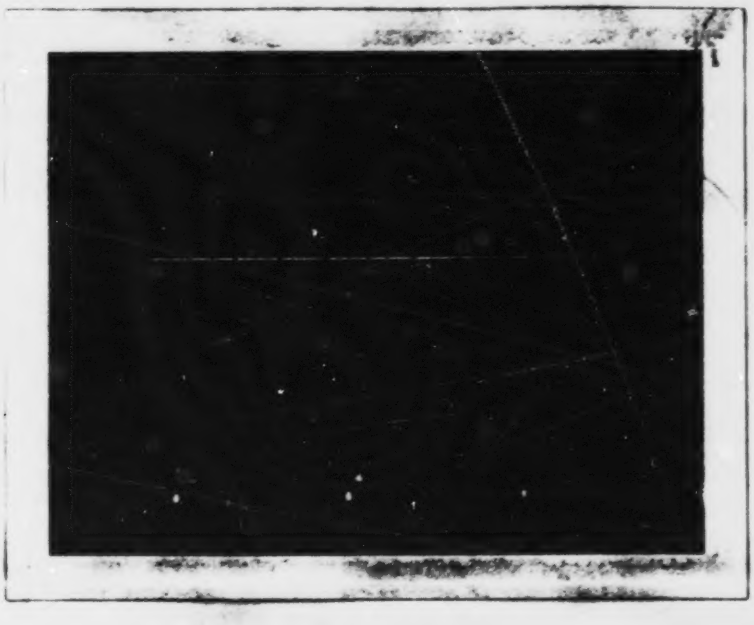


CONSTANT VOLUME

25g/m^3 coal dust C.B.

fusion wire vaporized

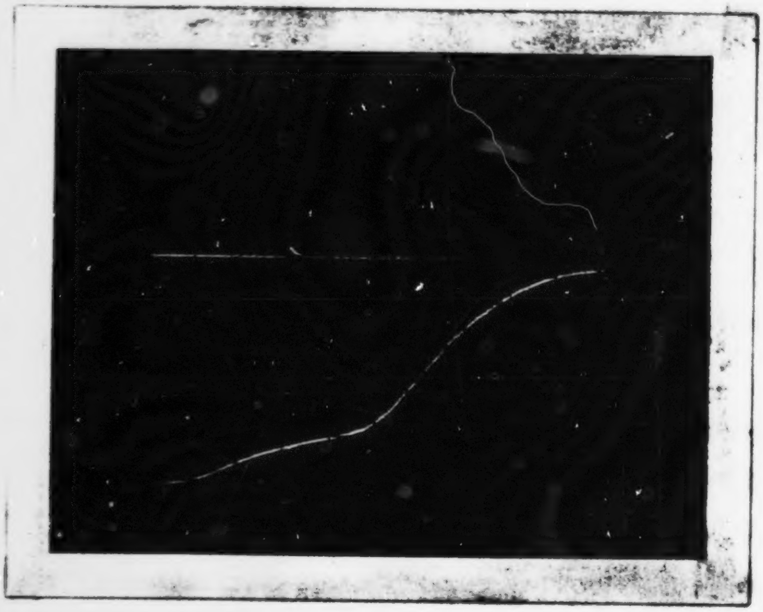
⇒ NO IGNITION



CONSTANT VOLUME 25g/m³ coal dust C.B.

1.3g ⇒ .65g/disp
20ms/div
.1V/div
10mV/div
60ms delay
Δp)max = 8psi
20KV-resistors
ION PROBE TRIGGERING
WAS SET INCORRECTLY

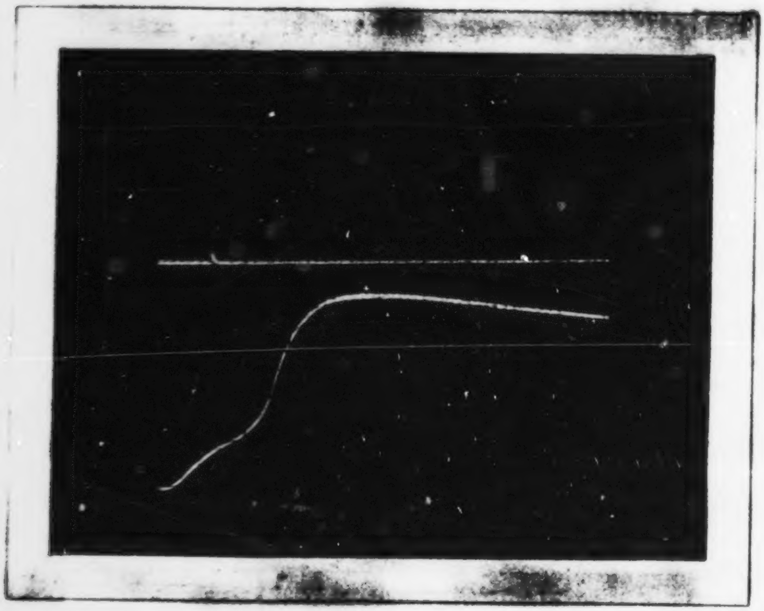
$\left(\frac{dp}{dt}\right) = 70$psi/s



CONSTANT VOLUME 15g/m³ coal dust C.B.

.8g ⇒ .4g/disp
50ms/div
.1V/div
10mV/div
60ms delay
Δp)max = 6.5psi
20KV-resistors
NO IONIZATION OF
PROBES BY FLAME

$\left(\frac{dp}{dt}\right) = 80$psi/s

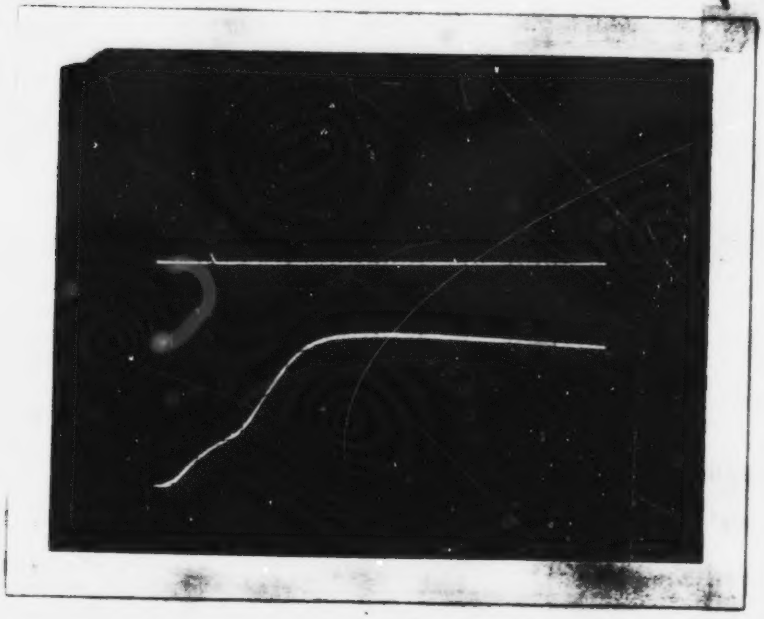


IGNITER CONSTANT VOLUME

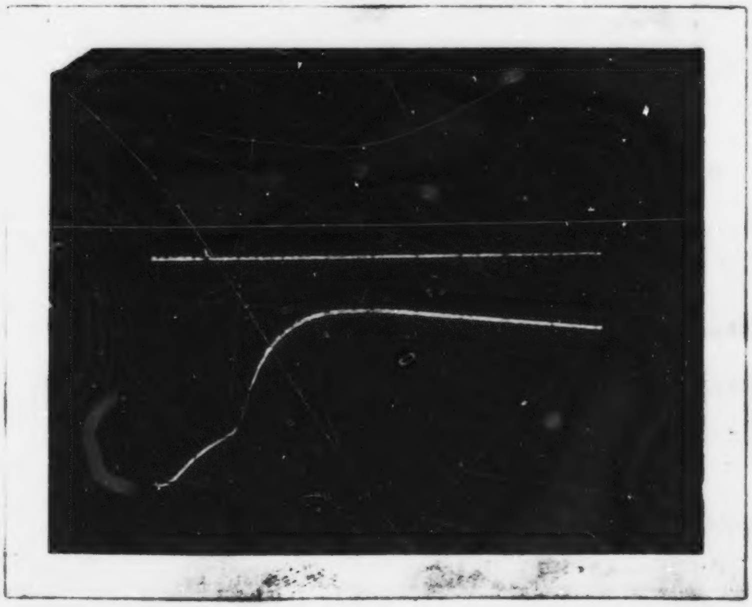
20 KV-resistors - 1.2g B.P. electricmatch

50ms/div
.1V/div
10mV/div

evac. pressure - 140 torr
dispersion pressure: 150psig



Δp)max= 4.6psi

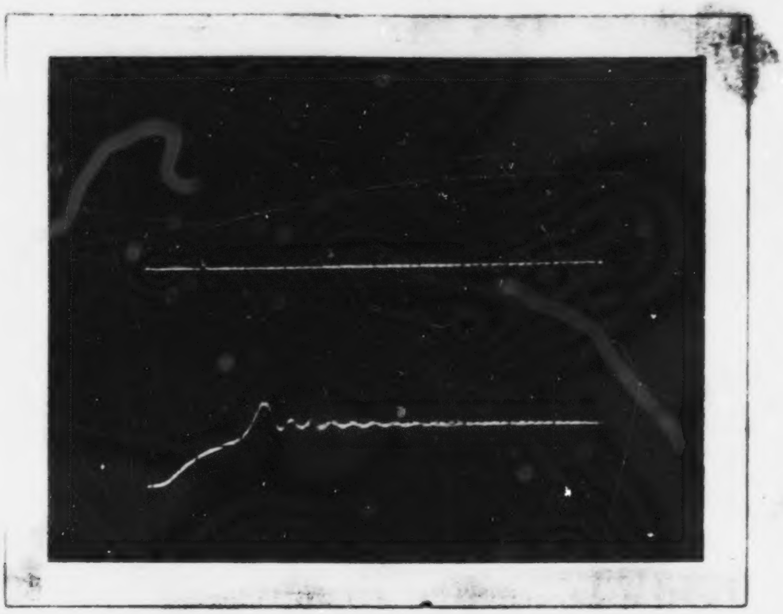


Δp)max =5.4psi

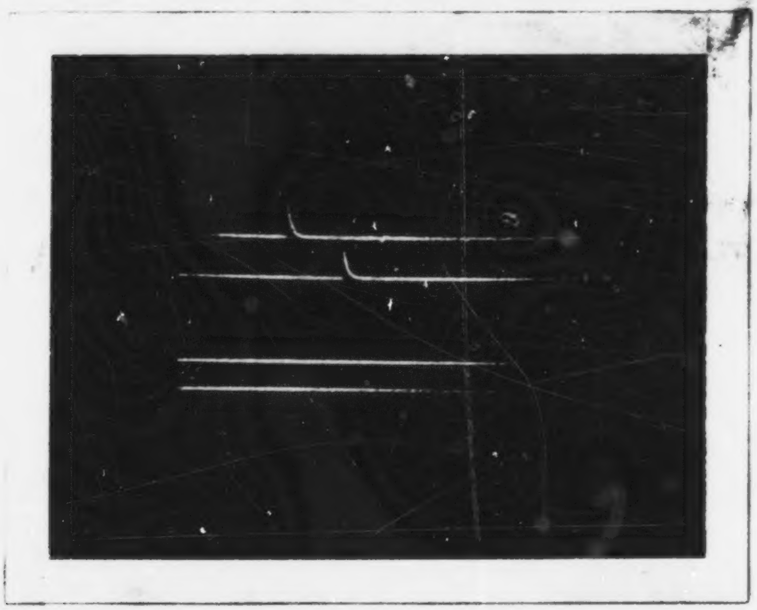
CONSTANT PRESSURE

430g/m^3 cornstarch

22.36g ⇒ 11.2g/disp



~~[illegible]~~
50ms/div
.1V/div
.10mV/div
60ms delay
Ignition: 1.2g BP
20kV-resistors

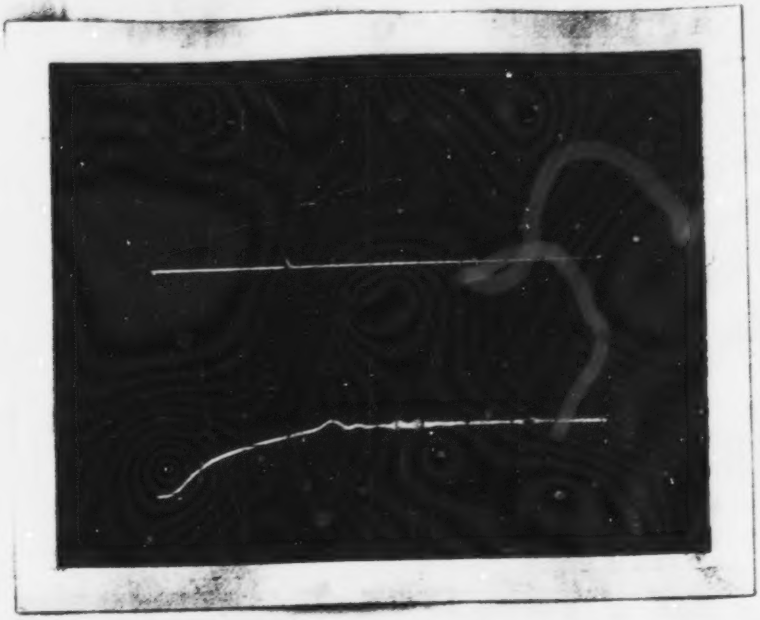


.2s/div
.1V/div

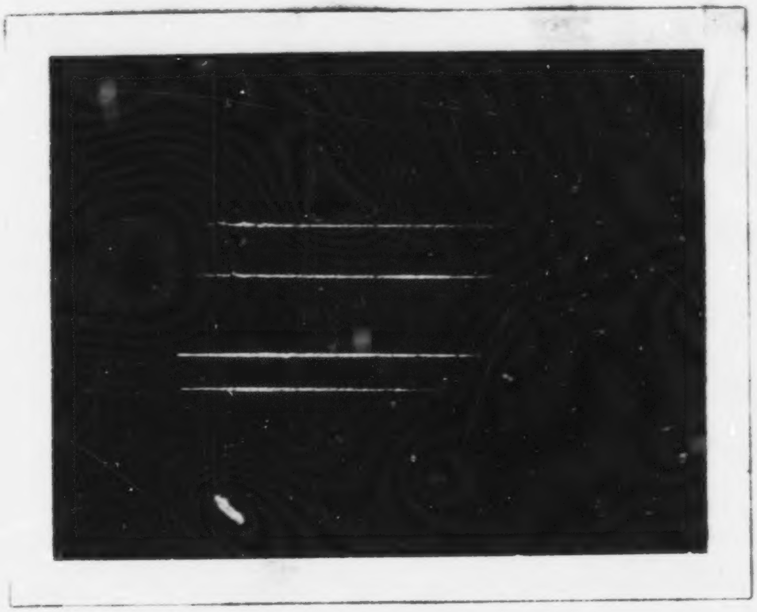
CONSTANT PRESSURE

400g/m^3 cornstarch
20.8g ⇒ 10.4g/disp.
50ms/div
.1V/div
. 10mV/div
150ms delay
20kV - resistors

X

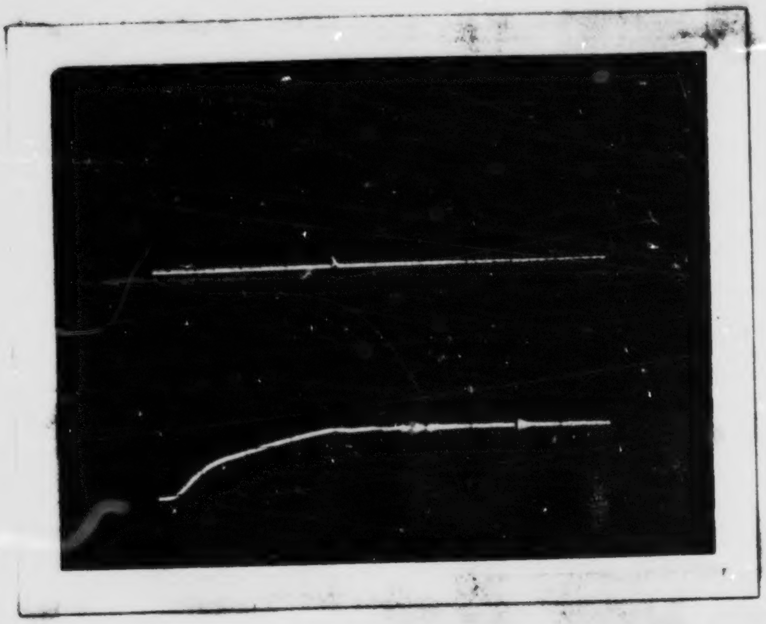


150ms delay
.5s/div
.1V/div
(3 probes)

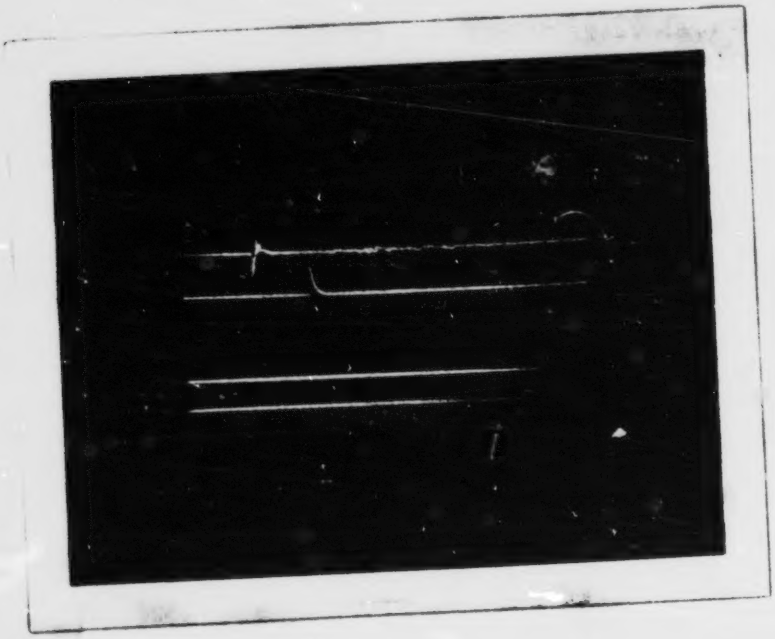


CONSTANT PRESSURE

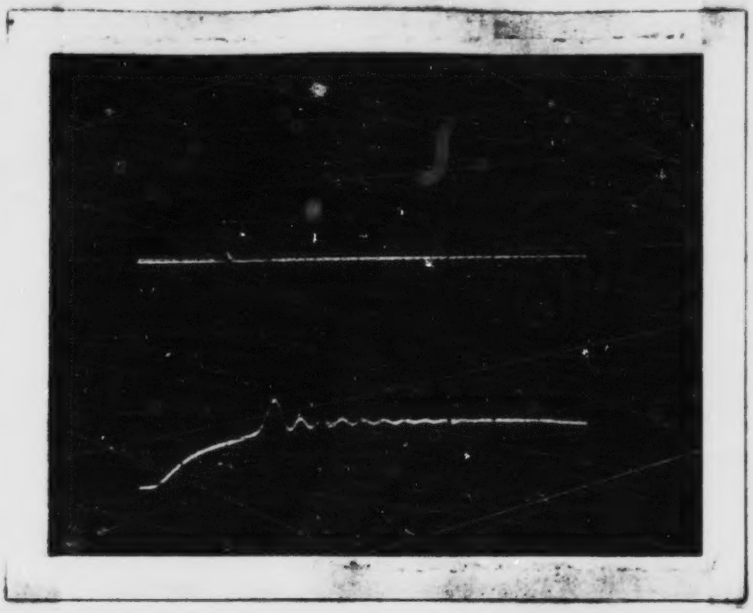
400g/m³ cornstarch
10.4g/drop
50ms/div
.1V/div
10mV/div
200ms delay
20KV-resistors



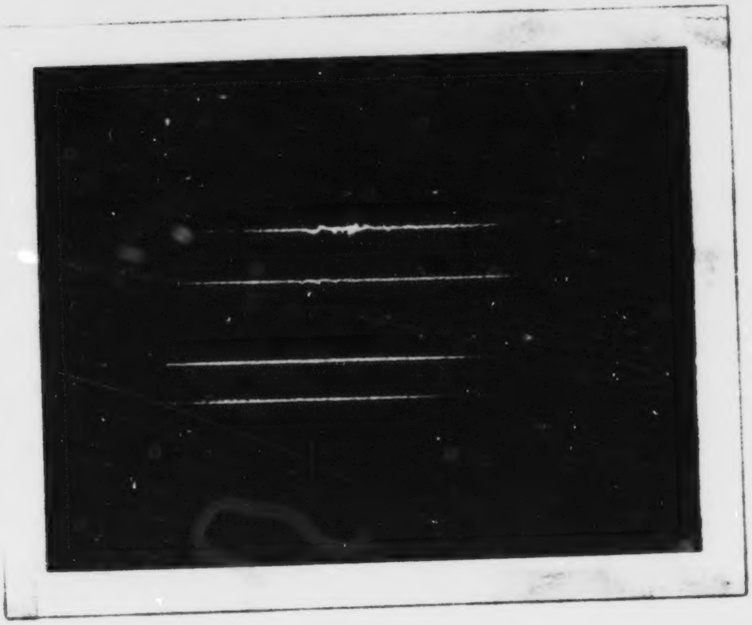
.2s/div
.1V/div



CONSTANT PRESSURE



400g/m^3 cornstarch
10.4g/disp
50ms/div
.1V/div
10mV/div
20kV-resistors
100ms delay

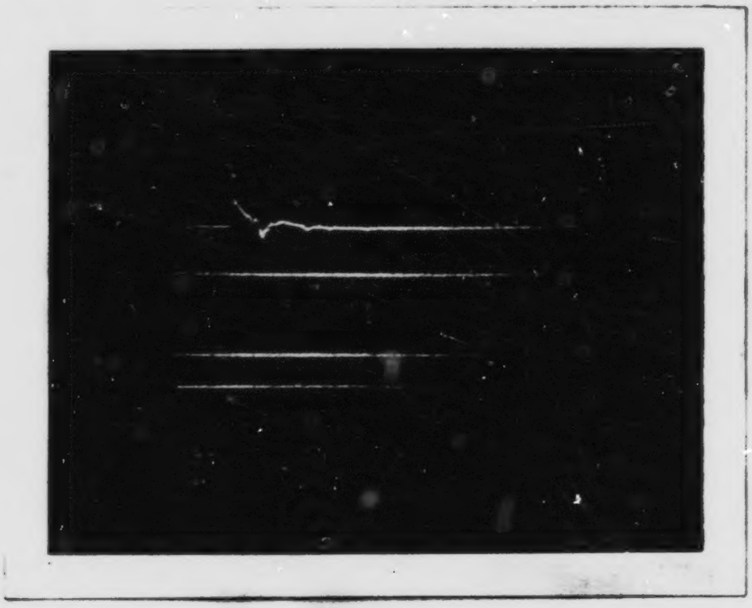


.2s/div
.1V/div

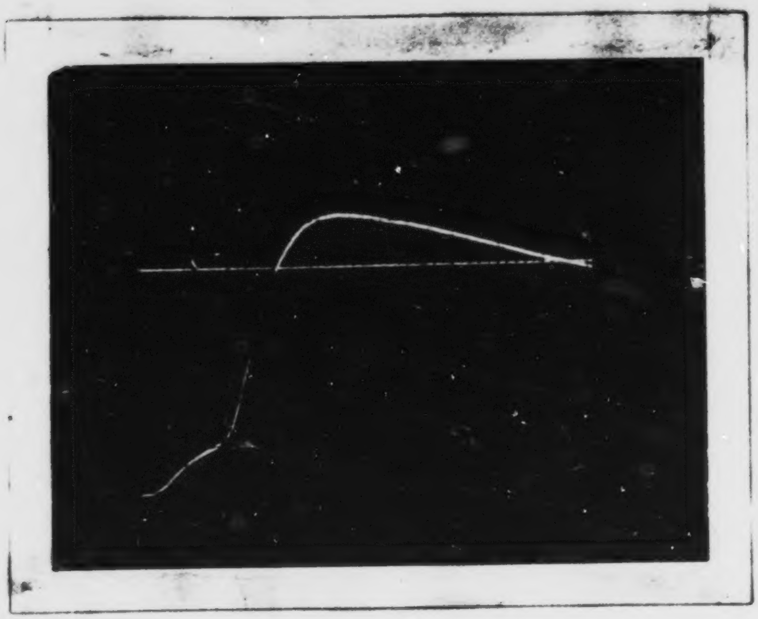
loud vibration

TO CHECK EFFECT OF HEATING ON
CAPE BRETON COAL DUST
heated 17hrs at "3" setting

CONSTANT VOLUME $40 g/m^3$ coal dust

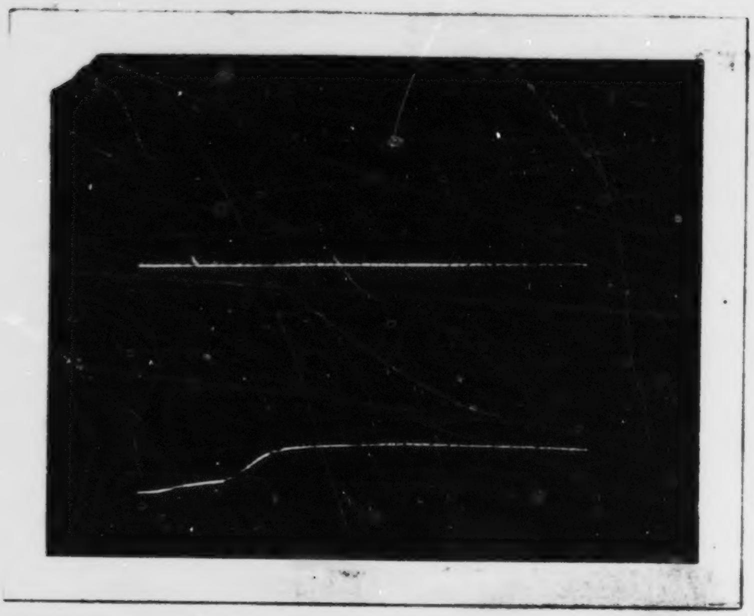


2.08g ⇒ 1.05 g/disp
50ms/div
.1V/div
60ms delay
Resid. pressure
top
bottom 14 psig



50ms/div
.1V/div
10mV/div
$\Delta p)_{max} = 10.3$ psi
$\left(\frac{dp}{dt}\right) = 99$ psi/s

CONSTANT VOLUME



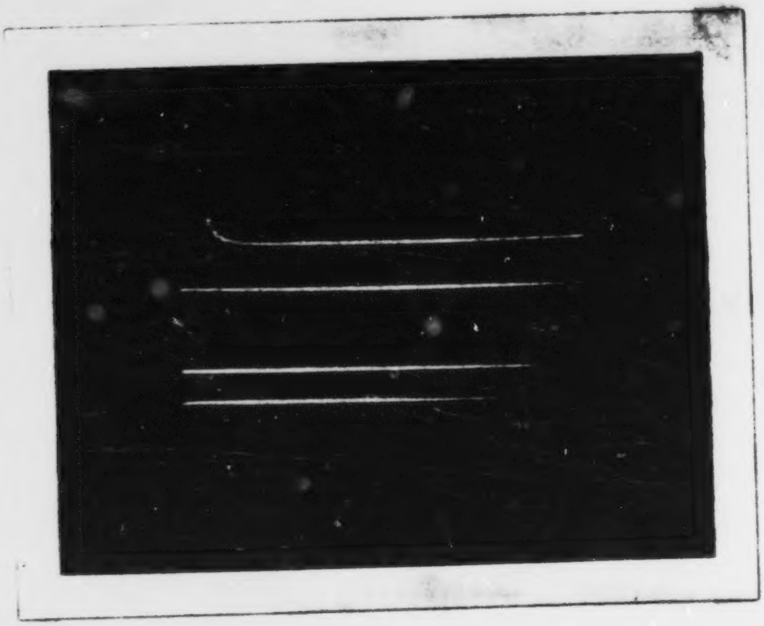
150g/m³ coal dust
heated for 17hrs
at "3" setting

50ms/div
.1V/div
50mV/div
60ms delay

Residual pressure:
top
bottom 12psig

$\Delta p_{max} \simeq 8.3$ psi

$\left(\frac{dp}{dt}\right) \simeq 41$ psi/s



.1s/div
.1V/div

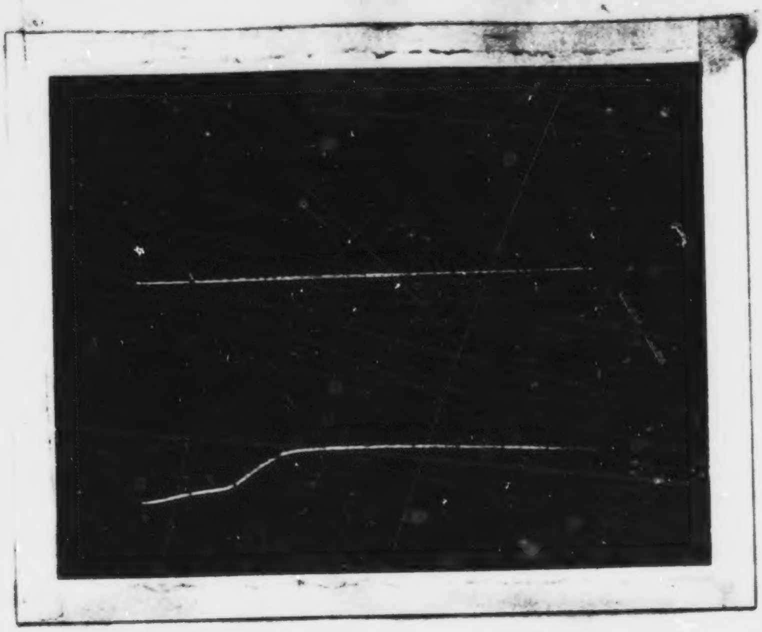
(perhaps bum
shot due to
vacuum pump on
when dust chamber
still open)

Should repeat

CONSTANT VOLUME

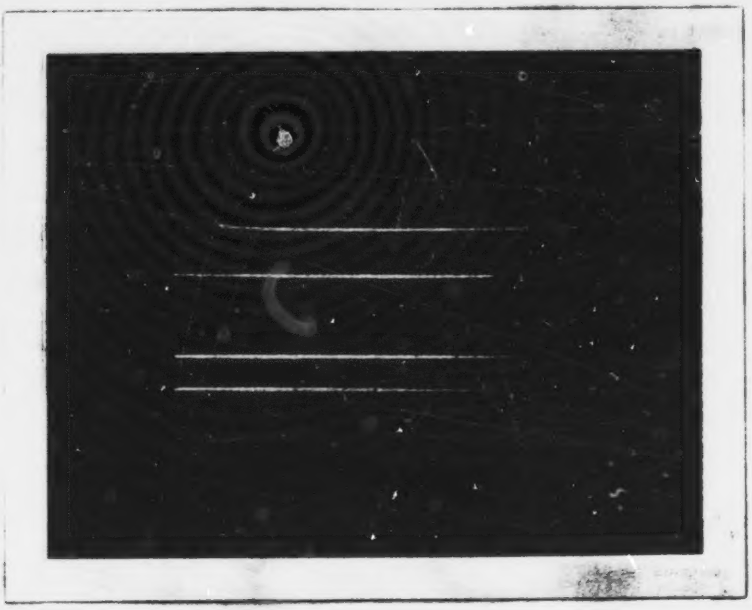
150g/m³ coal dust
C.B.
17hrs heated
50ms/div
.1V/div
50mV/div
60ms delay
$\Delta p|_{max} = 8.3$ psi
residual pressure:
top :
bottom : 12psig

7.8g ⇒ 3.9g/disp

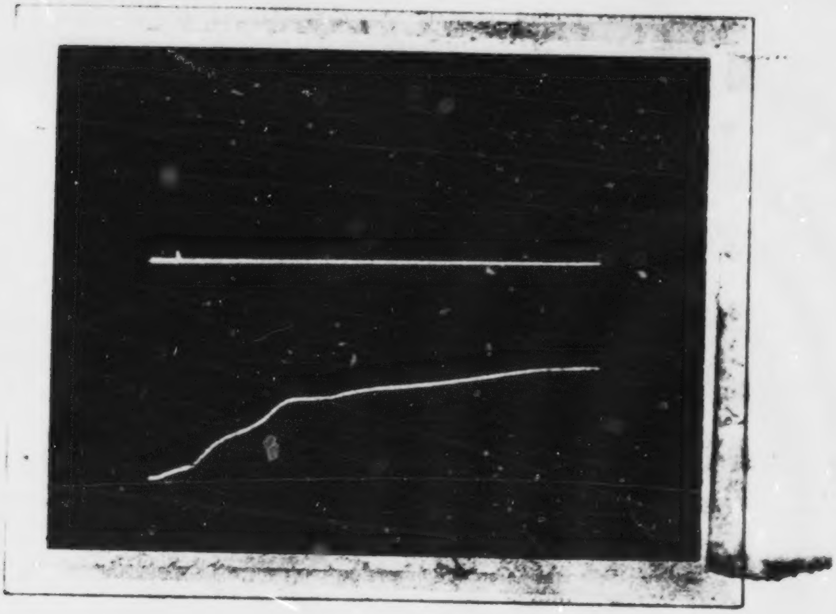


.1s/div
.1V/div

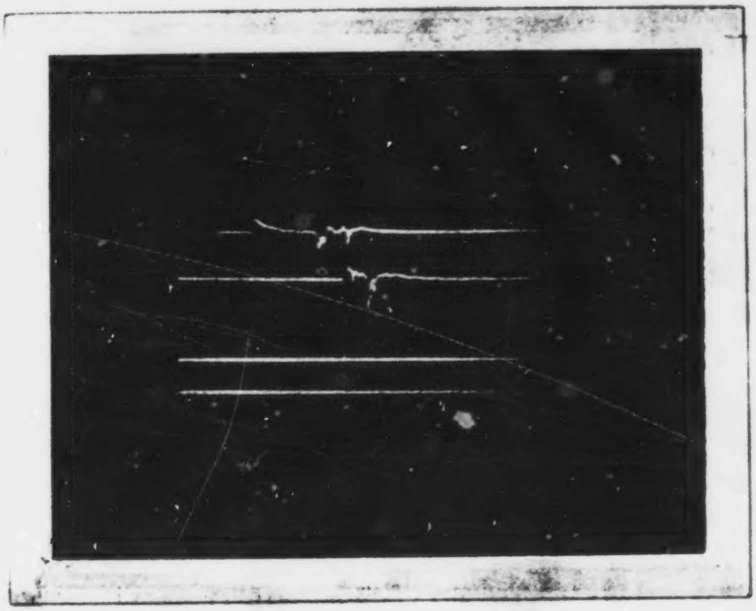
$\left(\frac{dp}{dt}\right) = 59$ psi/s



CONSTANT VOLUME UPWARD
250 g/m³ coal dust



13g ⇒ 6.5g/dis
.1s/div
.1V/div
50mV/div
$\Delta p)_{max} \approx 23$ p
P.P.: 30
30 psig
60ms delay
$\left(\frac{dp}{dt}\right) = 24$ psi/s

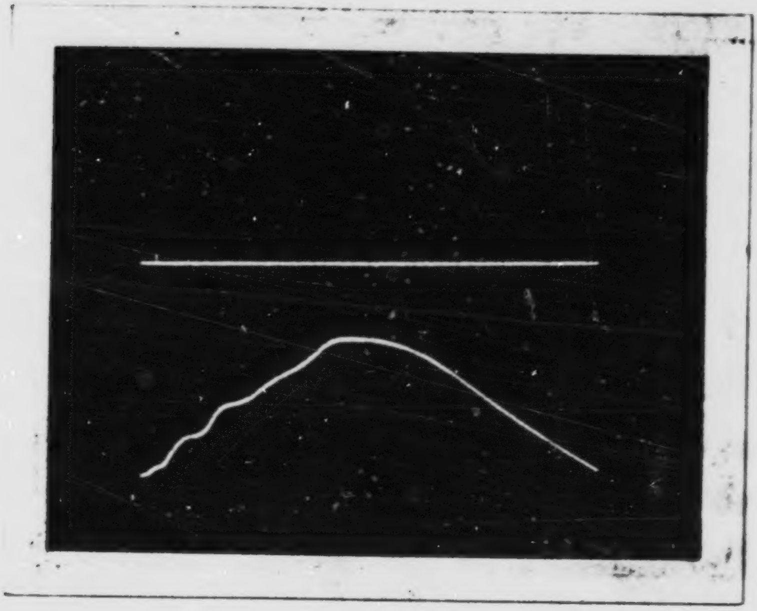


.1s/div
.1V/div

CONSTANT VOLUME UPWARD

350g/m³ coal dust

18.2g → 9.1g/disp



.2s/div
.1V/div
50mV/div
60ms delay

$\Delta p)_{max} = 30$ psi

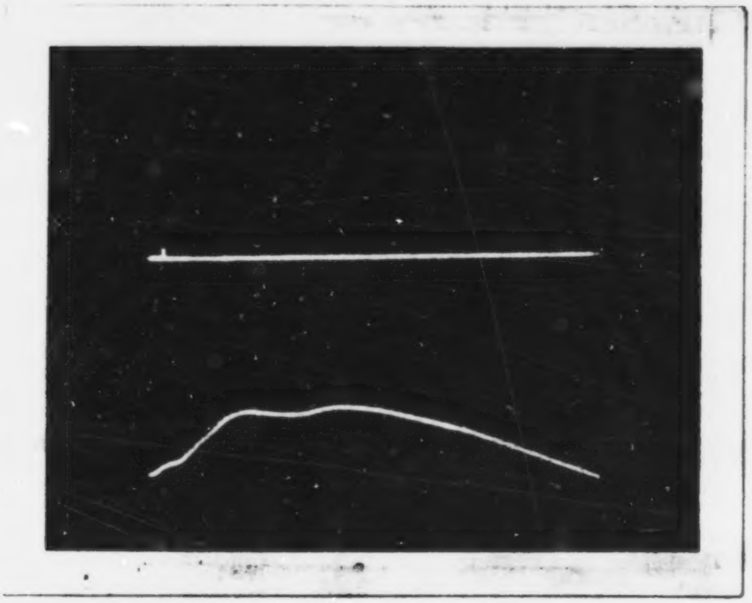
R.P. = 35psig
35

$\left(\frac{dp}{dt}\right) = 34$ psi/s

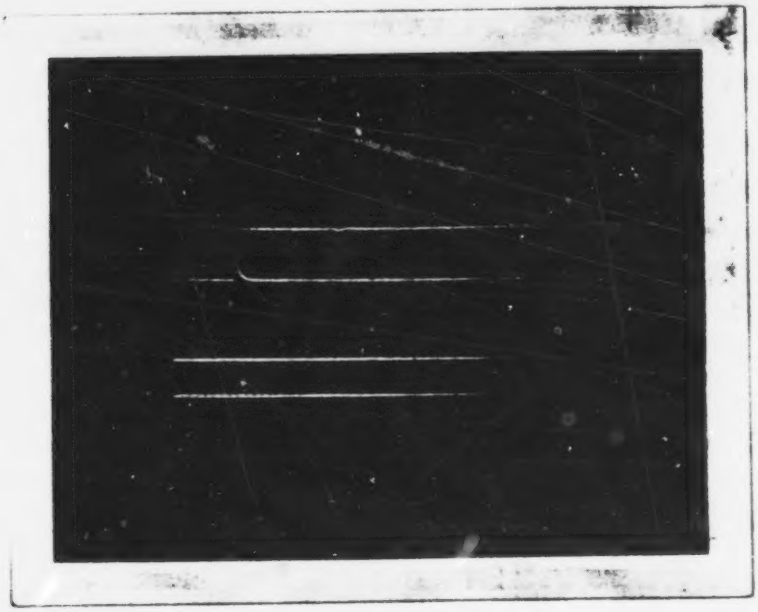
.1s/div
.1v/div

CONSTANT VOLUME UPWARD

400g/m³ coal dust   20.8g ⇒ 10.4g/disp



.2s/div
.1V/div
50mV/div
60ms delay
$\Delta p|_{max} = 13$ psi
$\left(\frac{dp}{dt}\right) = 22$ psi/s

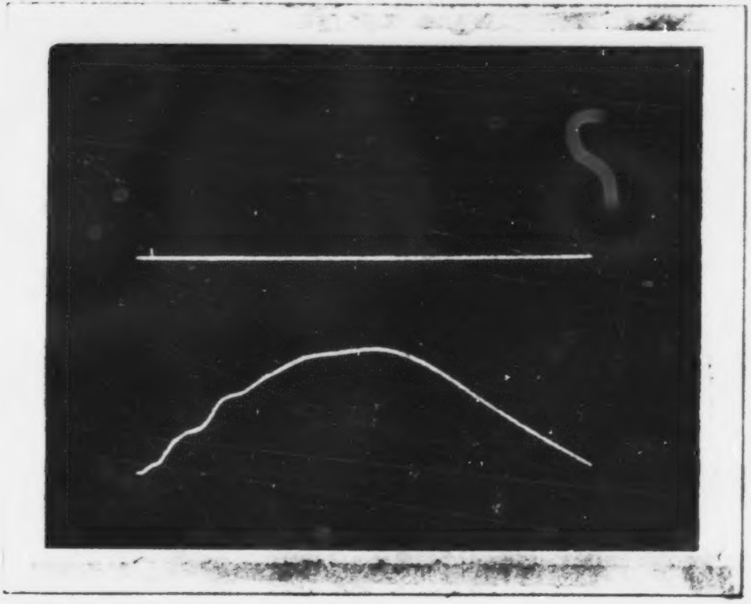


.2s/div
.1V/div

CONSTANT VOLUME UPWARD

450g/cm³ coal dust

23.4g → 11.7g/disp



.2s/div
.1V/div
50mV/div
60ms delay

$\Delta p)_{max} = 26$psi

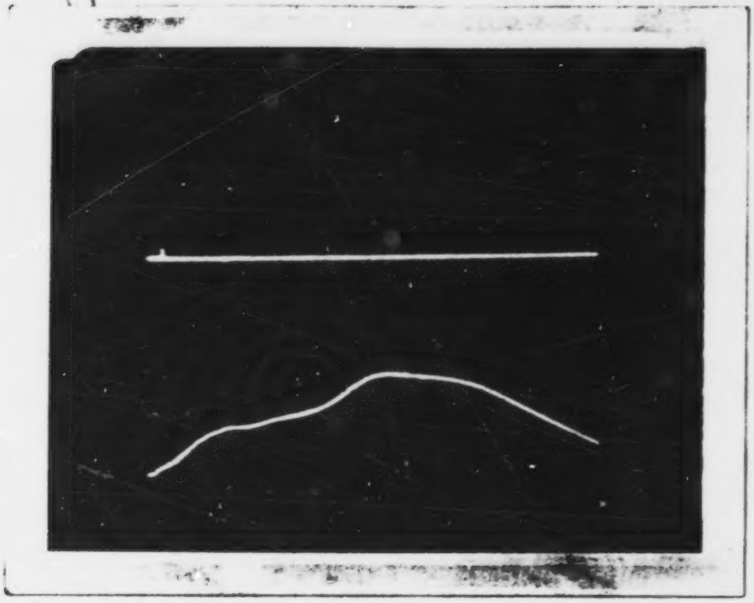
$\left(\frac{dp}{dt}\right) = 28$psi/s

.2s/div
.1V/div

CONSTANT VOLUME UPWARD

600g/m³ coal dust

31.2g ⇒ 15.6g/disp



.2s/div
.1V/div
50mV/div
60ms delay

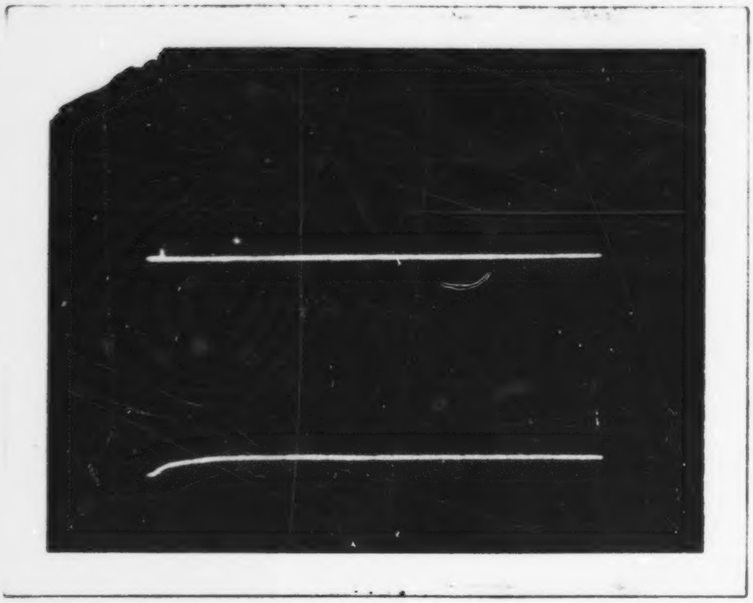
$\Delta p)_{max}$ = 20.7 psi

P.P. = 27 psig

$\left(\frac{dp}{dt}\right)$ = 19 psi/s

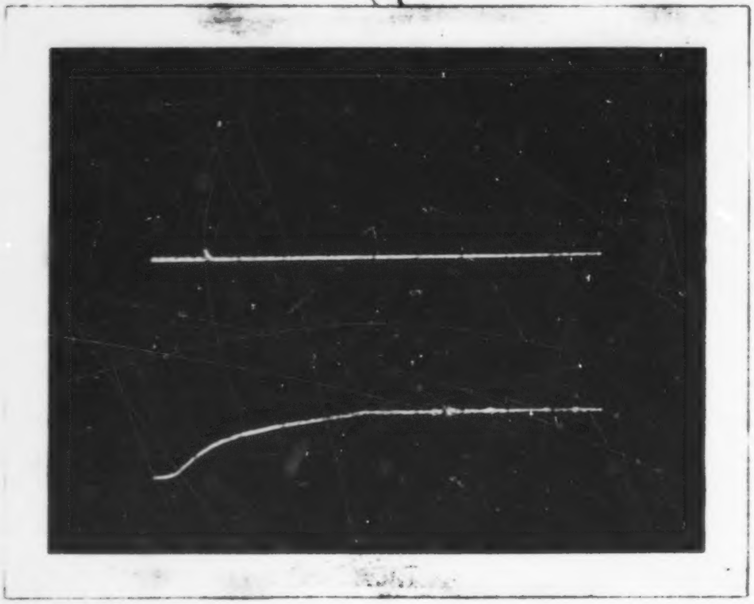
.2s/div
.1V/div

CONSTANT VOLUME UPWARD
600g/m³ coal dust



NO IGNITION

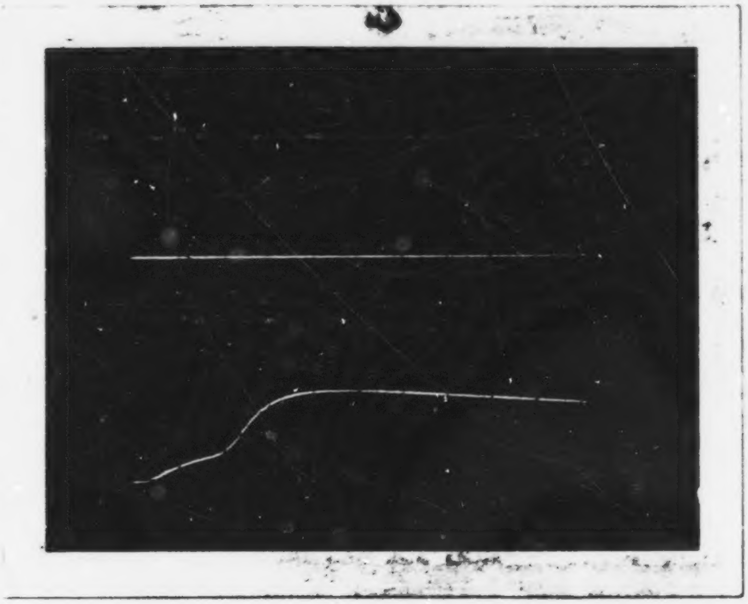
CONSTANT PRESSURE UPWARD
600g/m³ coal dust



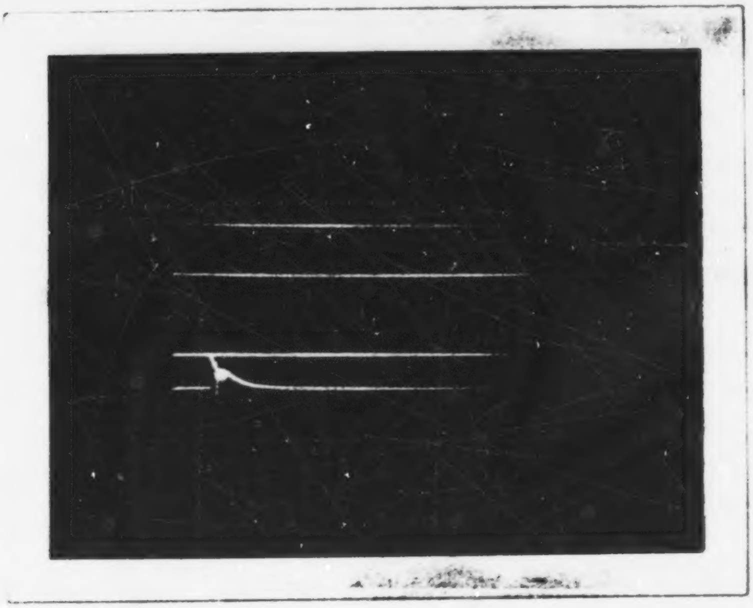
NO IGNITION

CONSTANT VOLUME DOWNWARD

40g/m³ coal dust



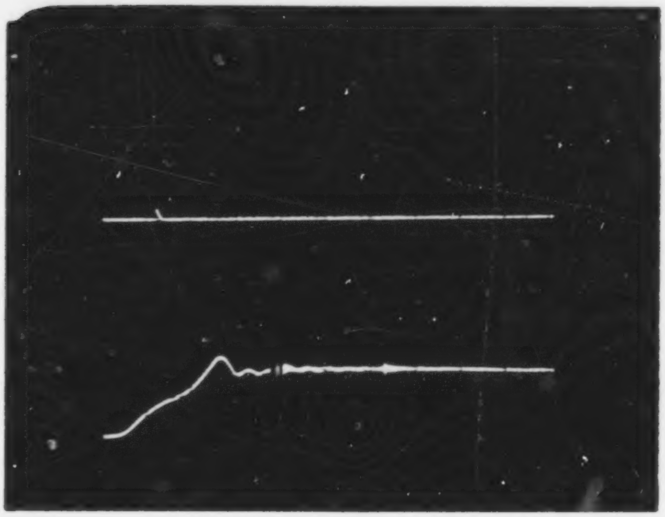
2.08g
⇒1.05g/dis
50ms/div
.1V/div
20mV/div
60ms delay
P.P. = 10psig
$\Delta p|_{max} = 6.4$psi
$\left(\frac{dp}{dt}\right) = 53$psi/s



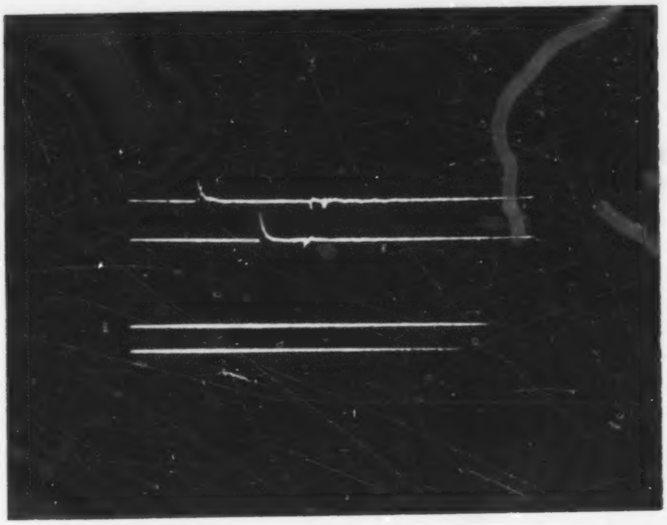
50ms/div
.1V/div

CONSTANT PRESSURE UPWARD

400g/m³ cornstarch 20.8g → 10.4g/disp



50ms/div
.1V/div
10mV/div
60ms delay

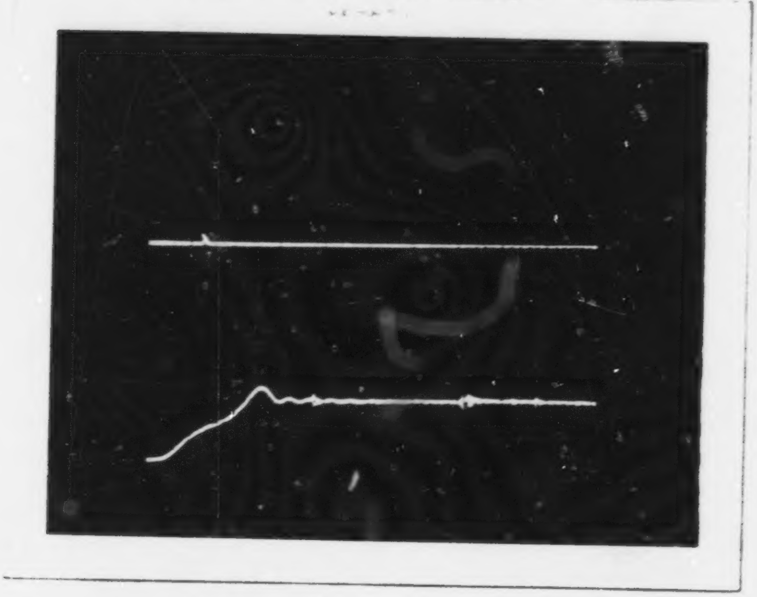


.2s/div
.1V/div

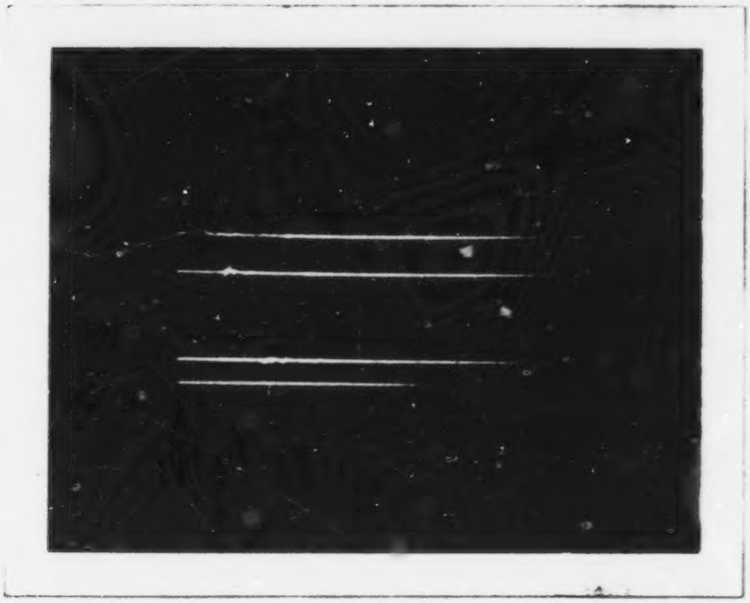
X

CONSTANT PRESSURE UPWARD

$500g/m^3$ cornstarch 26g → 13g/disp



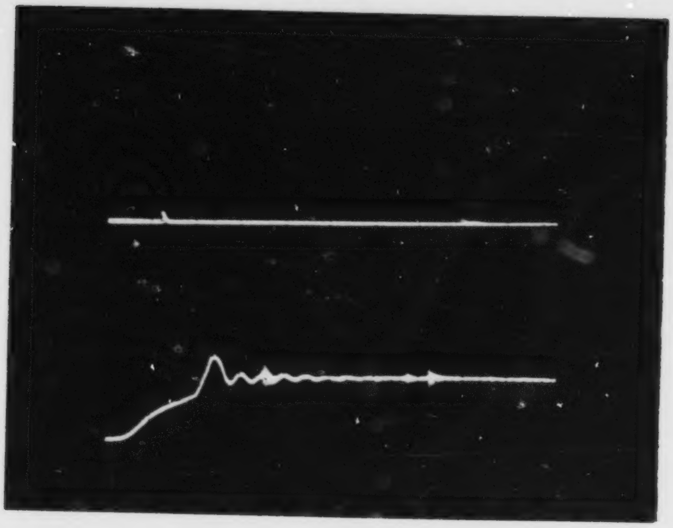
50ms/div
.1V/div
10mV/div
60msdelay



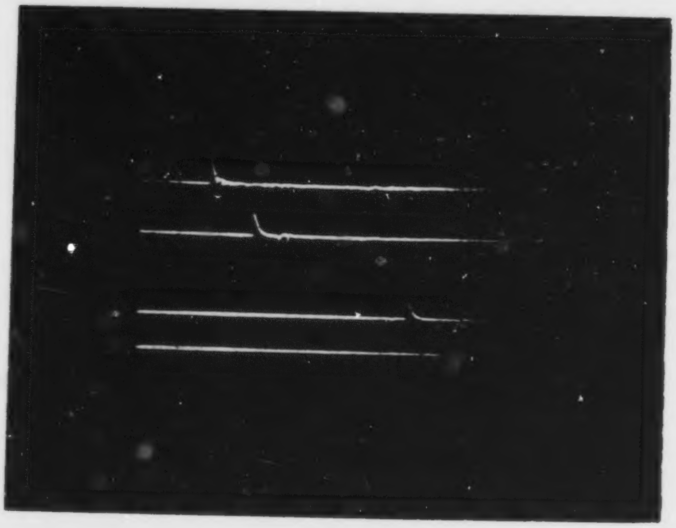
.5s/div
.1V/div

CONSTANT PRESSURE UPWARD

500g/cm³ cornstarch 26g⇒13g/disp



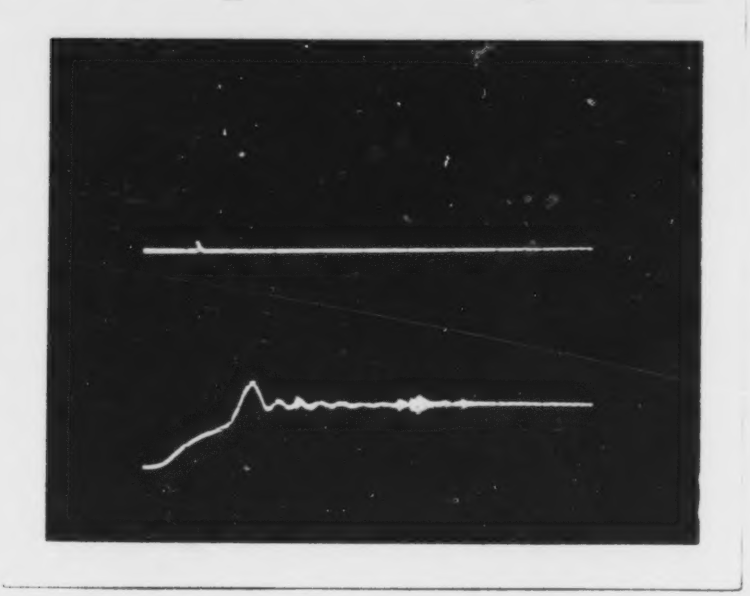
50ms/div
.1V/div
10mV/div
60ms delay



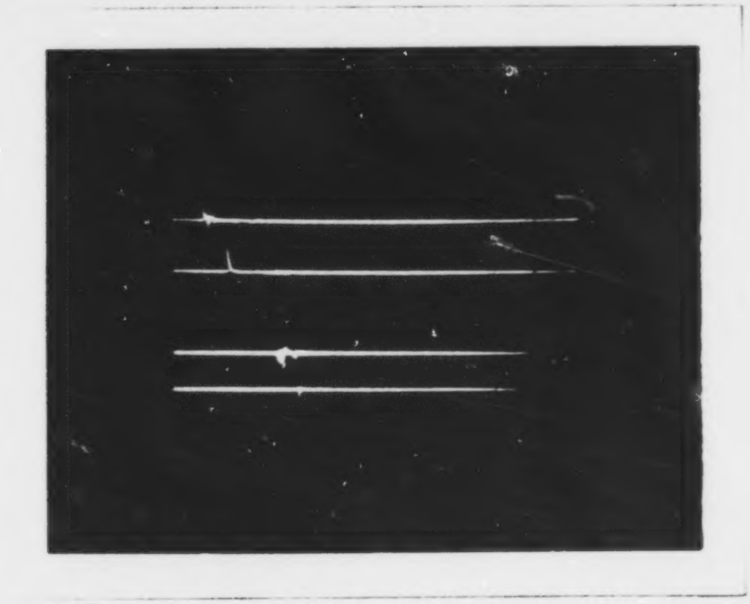
.2s/div
.1V/div

CONSTANT PRESSURE UPWARD

550 g/cm³ cornstarch 28.6g ⇒ 14.3g/disp



50ms/div
1V/div
10mV/div
60ms delay

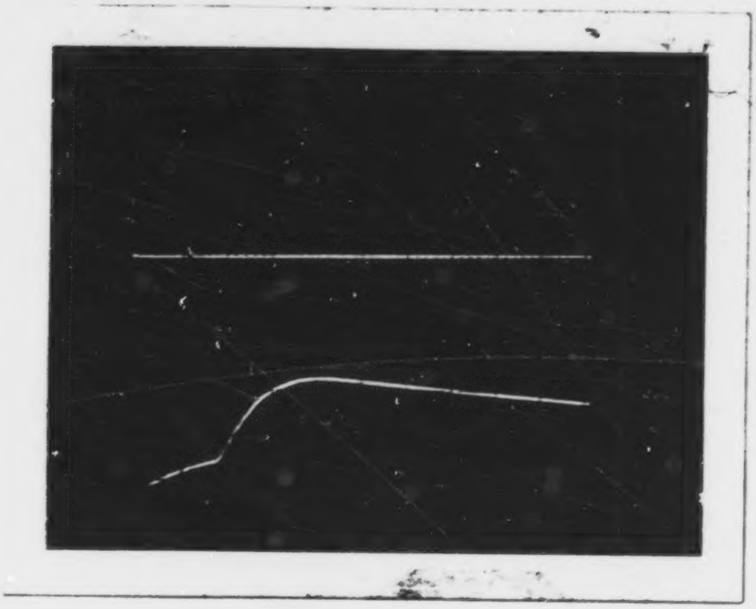


.5s/div
.1V/div

CONSTANT VOLUME DOWNWARD

40g/m³ coal dust

2.08g ⇒ 105g/disp



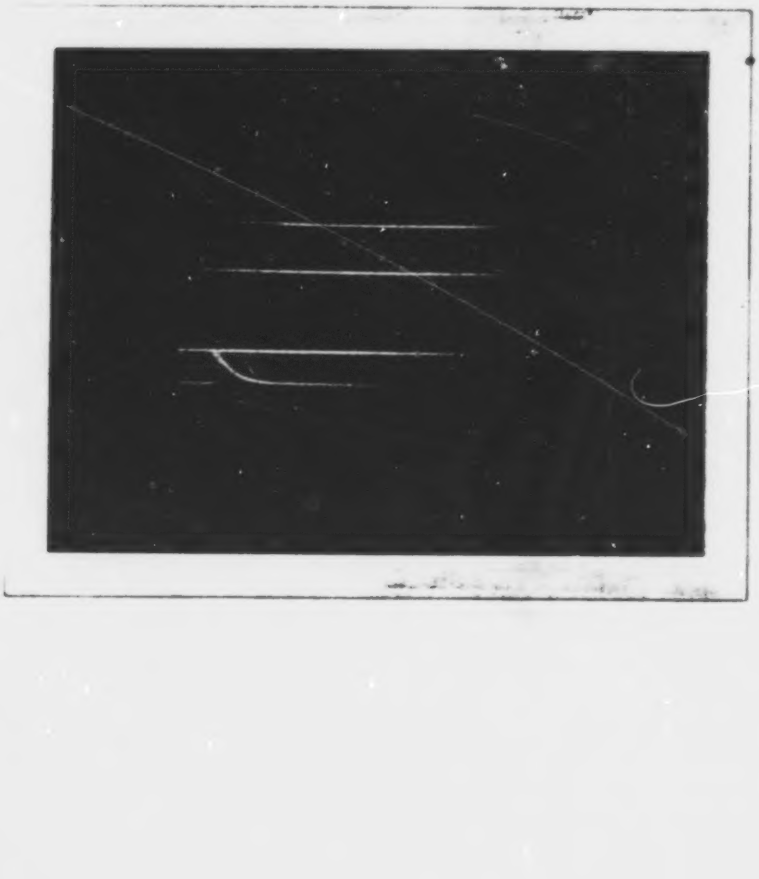
50ms/div
.1V/div
20mV/div

60ms delay

$\Delta p|_{max} = 7.9$ psi

$\left(\overline{\frac{dp}{dt}}\right) = 90$ psi/s

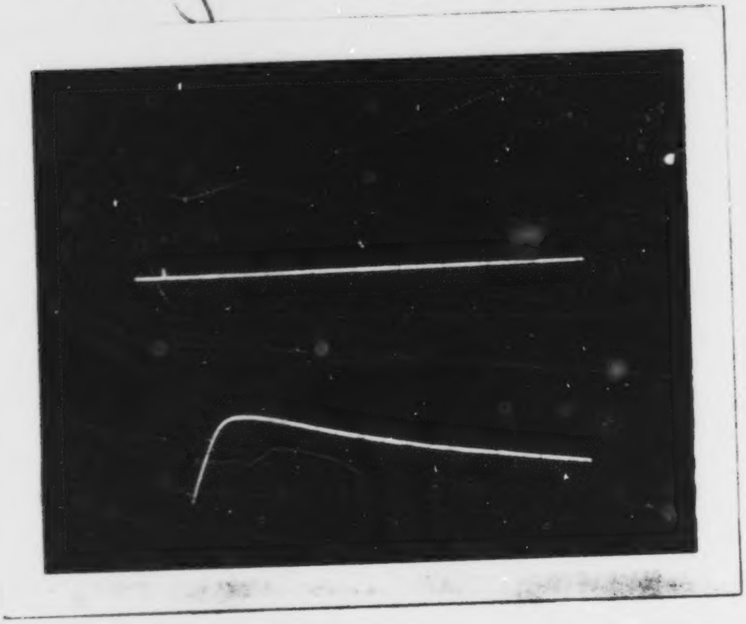
R.P. = 10psig



50ms/div
1V/div

CONSTANT VOLUME DOWNWARD

100g/m³ coal dust   5.2g ⇒ 2.6g/disp

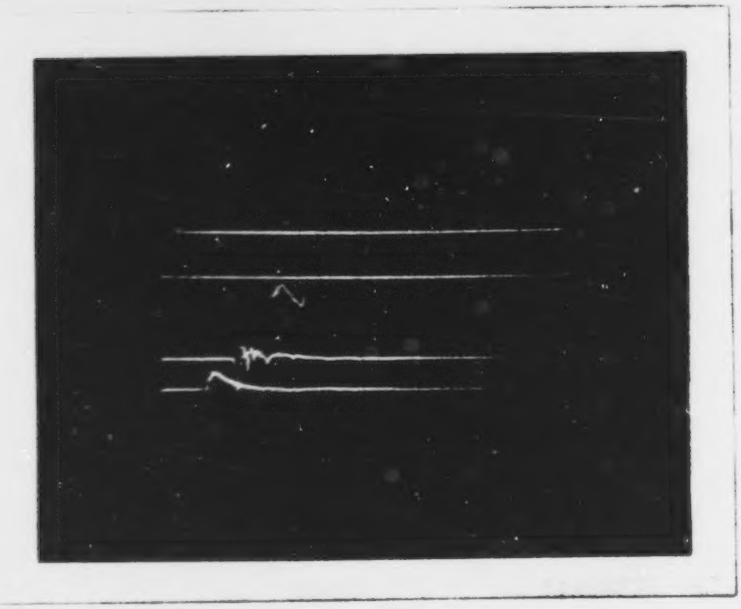


.1s/div
.1V/div
20mV/div
60ms delay

$\Delta p|_{max} \approx 11.5$ psi ⊛

R.P. = 11psig

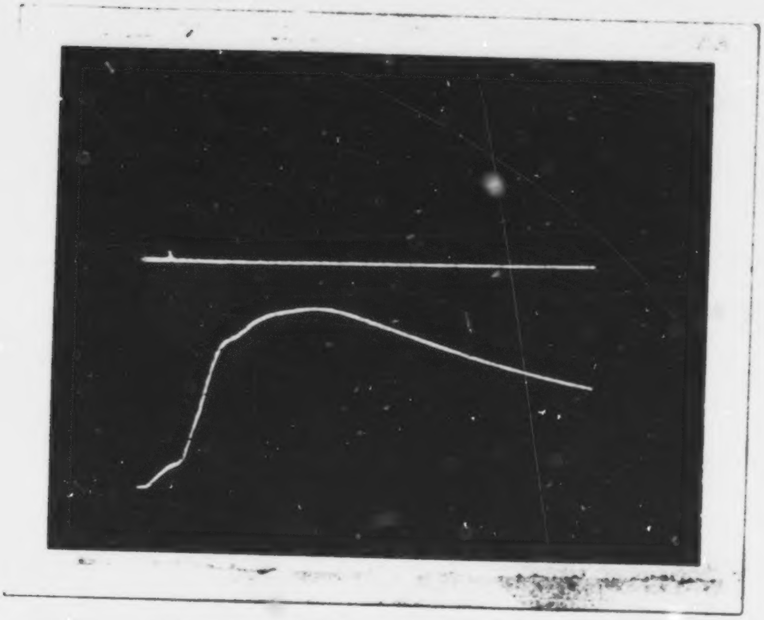
$\left(\frac{dp}{dt}\right) = 115$ psi/s



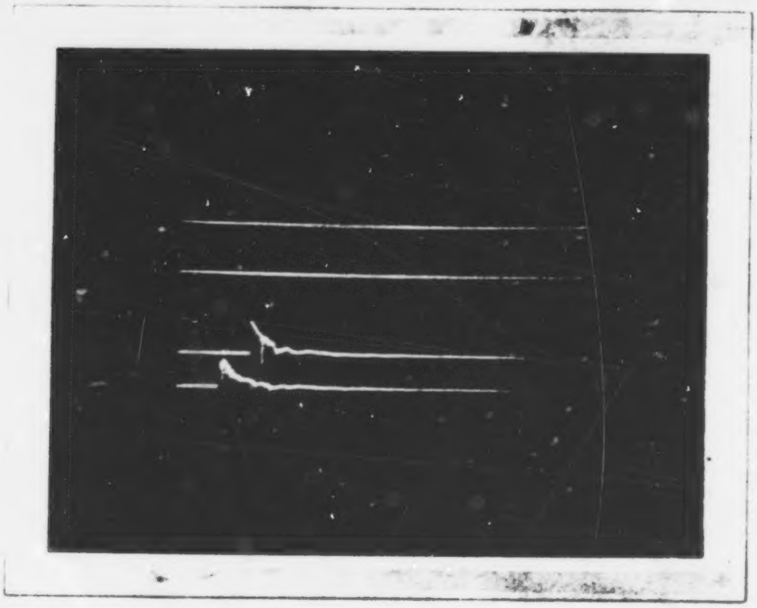
50ms/div
.1V/div

CONSTANT VOLUME DOWNWARD

150g/m³ coal dust 7.8g → 3.9g/disp



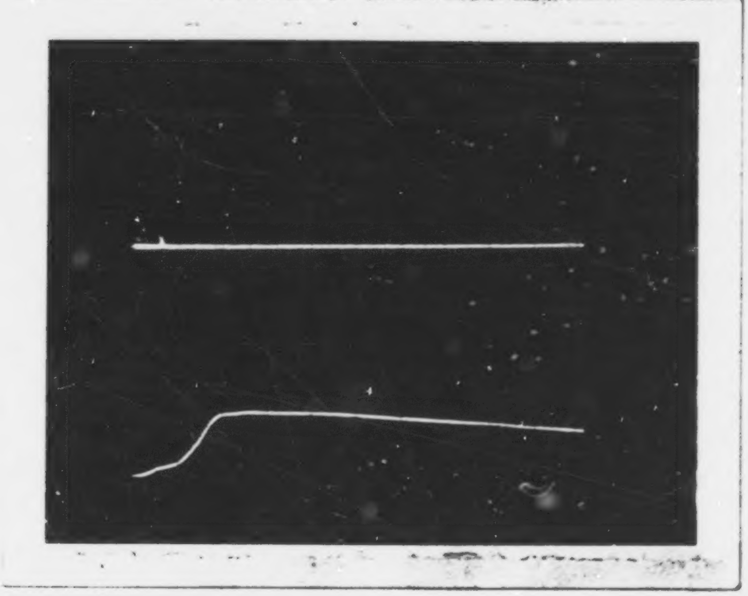
.1s/div
.1V/div
20mV/div
60ms delay
$\Delta p|_{max}$ = 14.5psi
R.P. = 10psig
$\left(\frac{dp}{dt}\right)$ = 72psi/s



50ms/div
.1V/div

CONSTANT VOLUME DOWNWARD

200dm³ coal dust 10.4g ⇒ 5.2g/disp

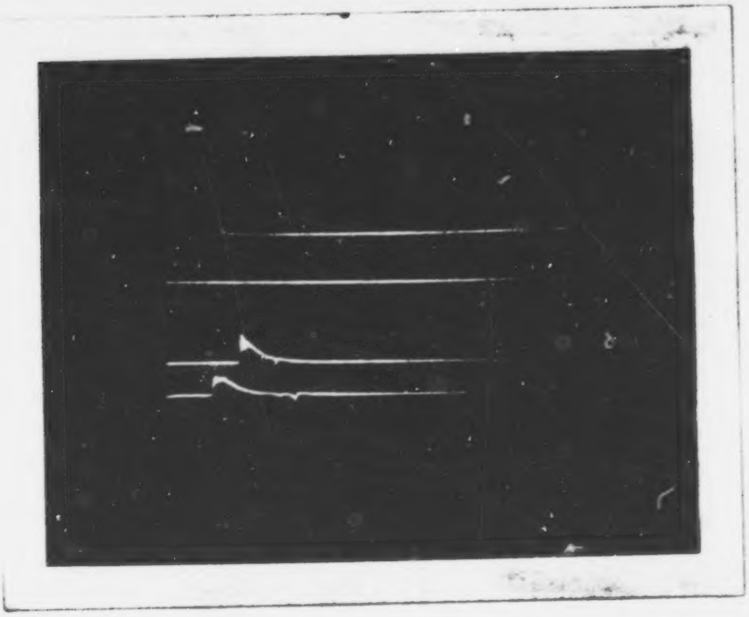


.1s/div
.1V/div
50mV/div
60ms delay

$\Delta p|_{max} = 12.5$ psi

R.P. = 10psig

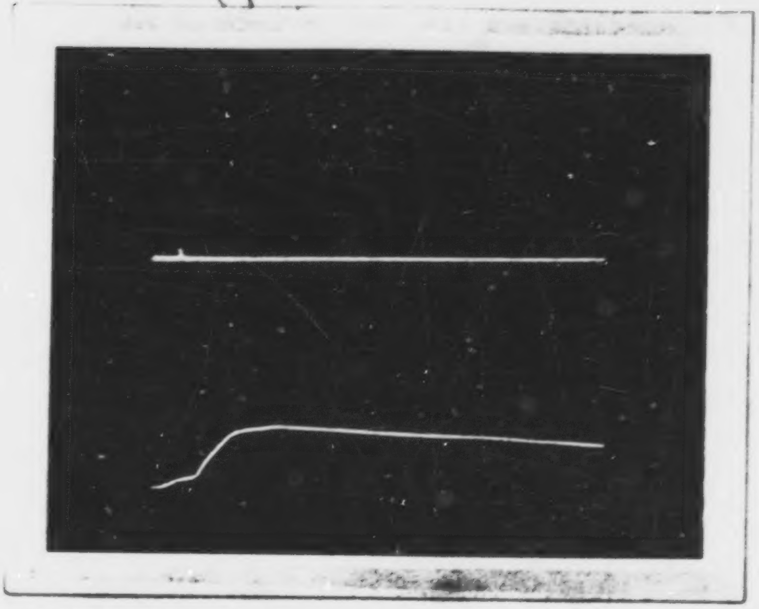
$\left(\frac{dp}{dt}\right) = 138$ psi/s



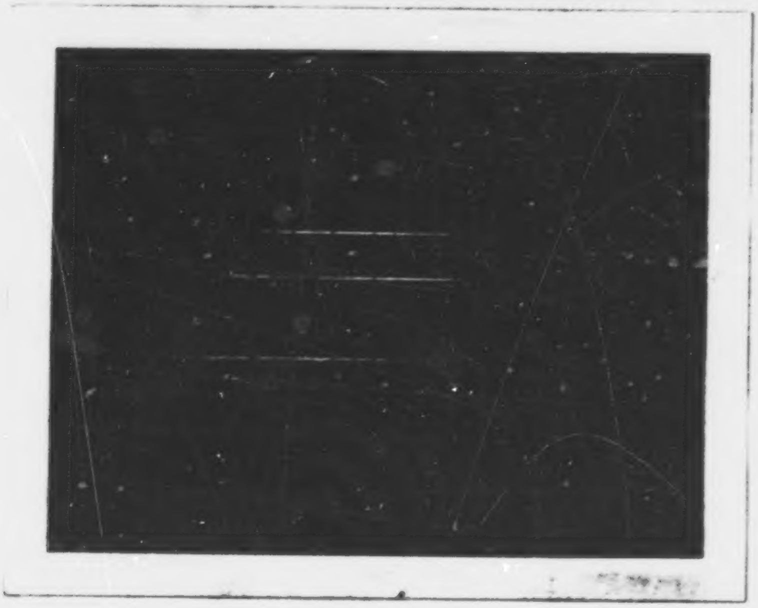
50ms/div
.1V/div

CONSTANT VOLUME DOWNWARD

300g/m³ coal dust 15.6g ⇒ 7.8g/disp



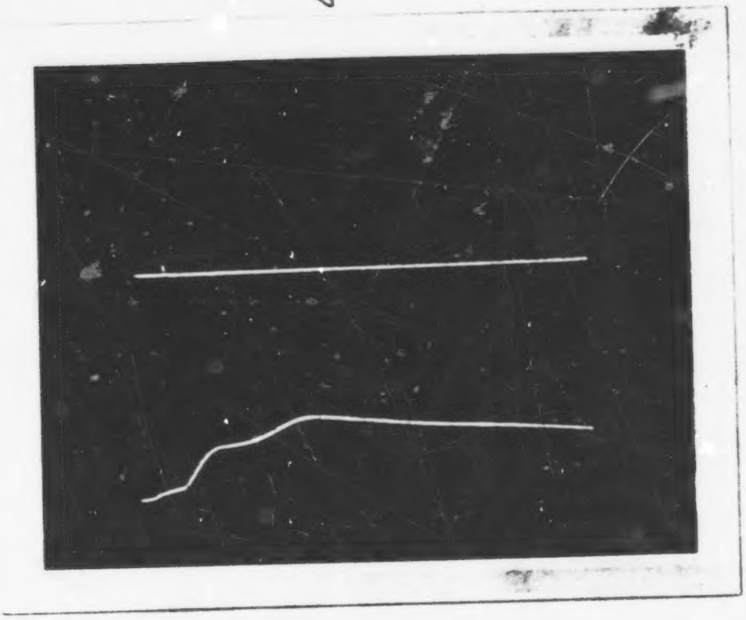
.1s/div
.1V/div
50mV/div
60ms delay
$\Delta p)_{max}$ = R4ps
R.P. = 11 psig
$\left(\overline{\frac{dp}{dt}}\right) = 82$ psi/s



50ms/div
.1V/div

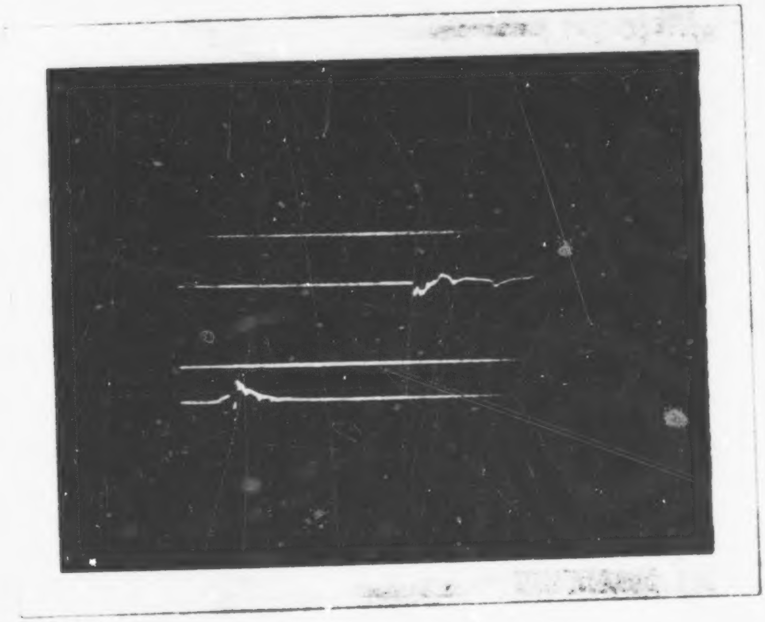
CONSTANT VOLUME DOWNWARD

450 g/m^3 coal dust   23.4g → 11.7g/disp



.1s/div
.1V/div
50mV/div
60ms delay

$\Delta p|_{max} = 16.5$ psi
R.P. = 15 psig
$\left(\frac{dp}{dt}\right) = 68$ psi/s

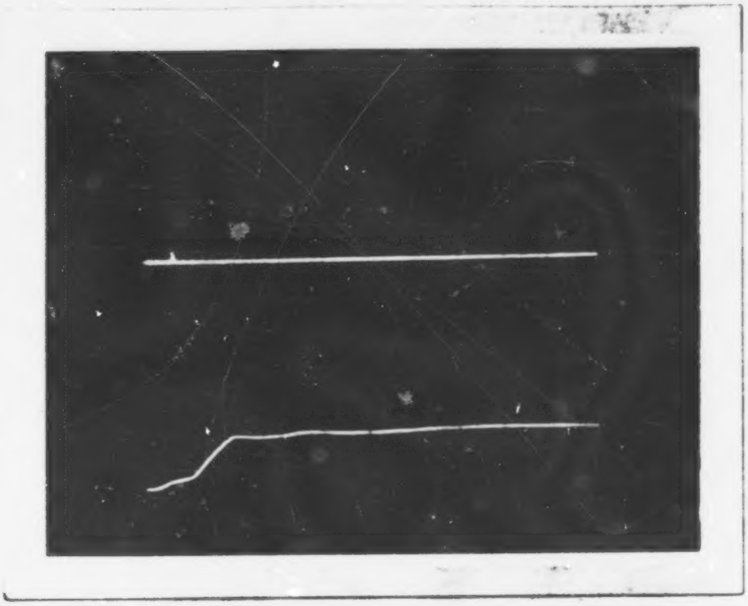


50ms/div
.1V/div

CONSTANT VOLUME DOWNWARD

500g/m³ coal dust

26g ⇒ 13g/disp

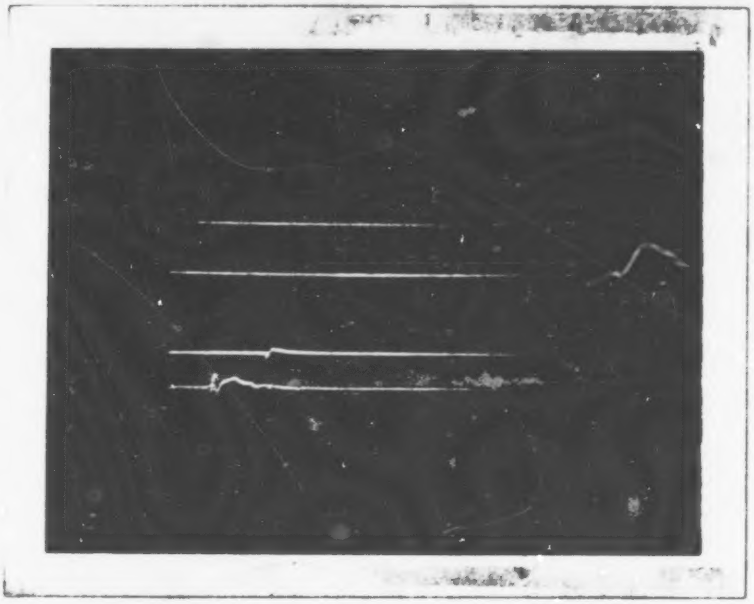


.1s/div
.1V/div
50mV/div
60ms delay

$\Delta p)_{max}$ = 11.4psi

R.P. = 16psig

$\overline{\left(\frac{dp}{dt}\right)}$ = 12psi/s

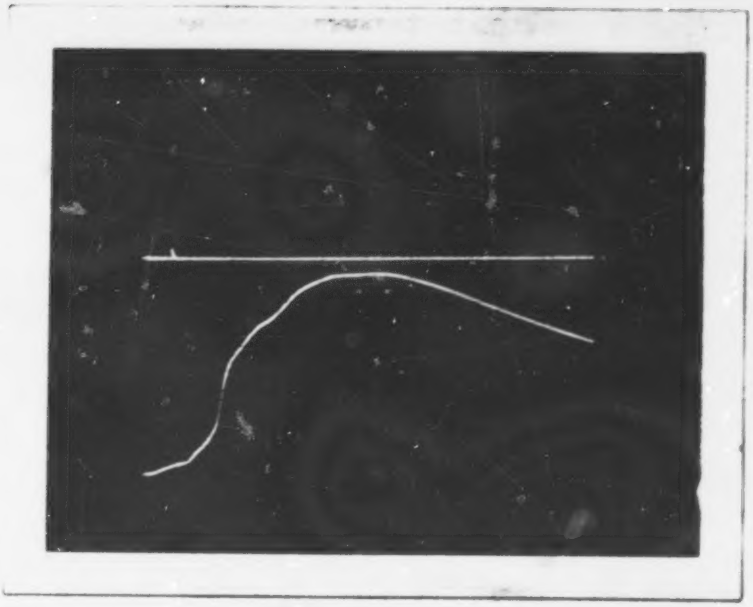


50ms/div
.1V/div

CONSTANT VOLUME UPWARD

200g/m³ cornstarch

10.4g → 5.2g/disp



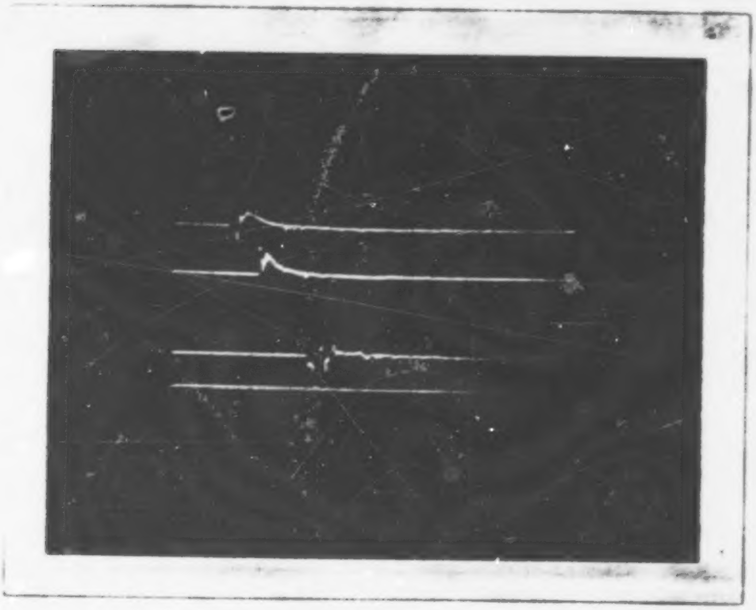
.1s/div
.1V/div
50mV/div
60ms delay

$\Delta p)_{max} = 43.4$ psi

R. P. $^{38}_{19}$ psig

$\left(\frac{\overline{dp}}{dt}\right) = 191$ psi/s

50ms/div
.1V/div



CONSTANT VOLUME UPWARD

250g/m³ cornstarch

13g ⇒ 6.5g/disp

.1s/div

.1V/div

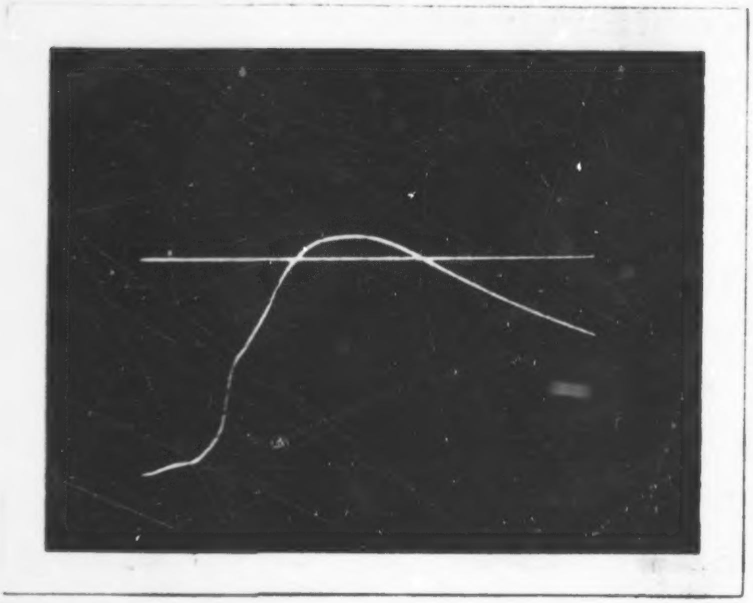
50mV/div

60ms delay

ΔP_{max} = 51.7 psi

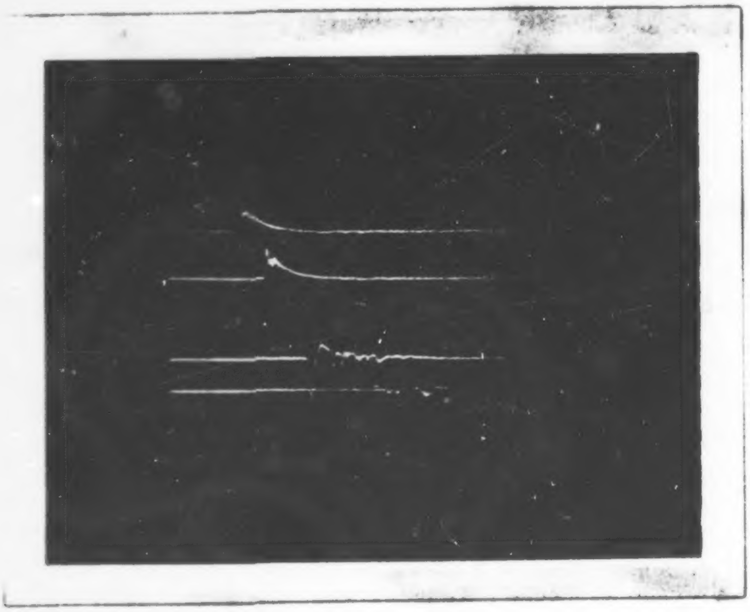
R.P. $\begin{smallmatrix}30\\38\end{smallmatrix}$ psig

$\left(\frac{dP}{dt}\right|$ = 253 psi/s



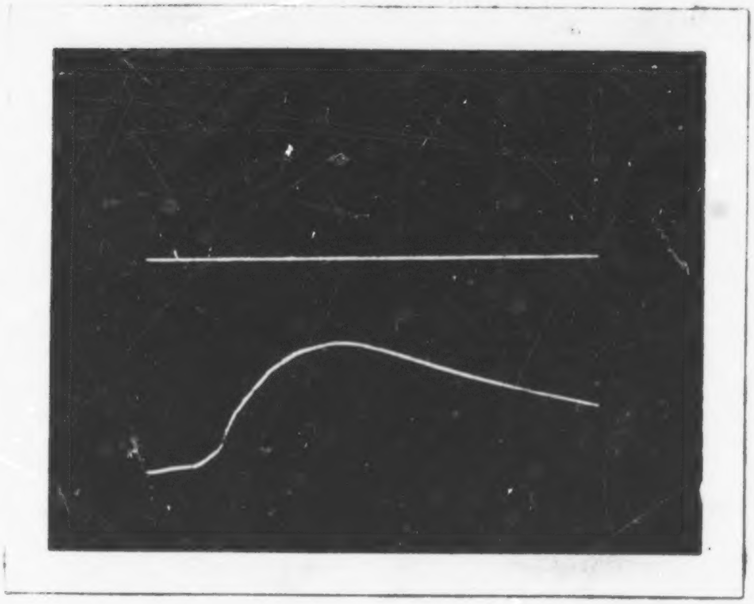
50ms/div

.1V/div

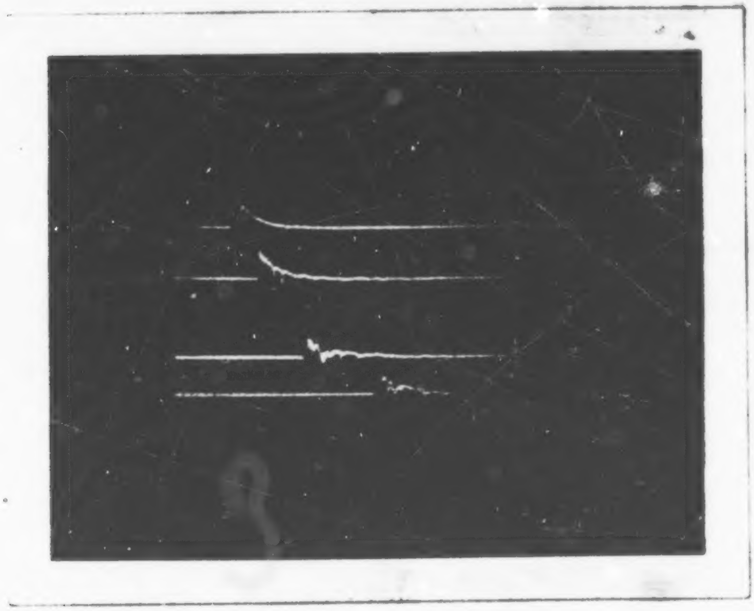


CONSTANT VOLUME UPWARD

300g/cm³ cornstarch 15.6g ⇒ 7.8g/disp



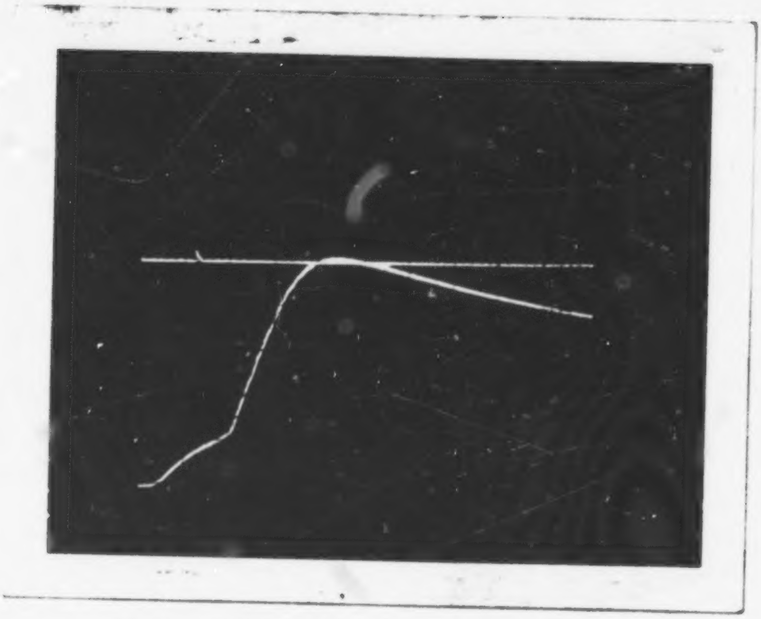
.1s/div
.1V/div
.1V/div
60 ms delay
$\Delta P|_{max} = 57.9$ p
R.P. = $\overset{45}{0}$ psig
$\left(\frac{dp}{dt}\right) = 238$ psi/s



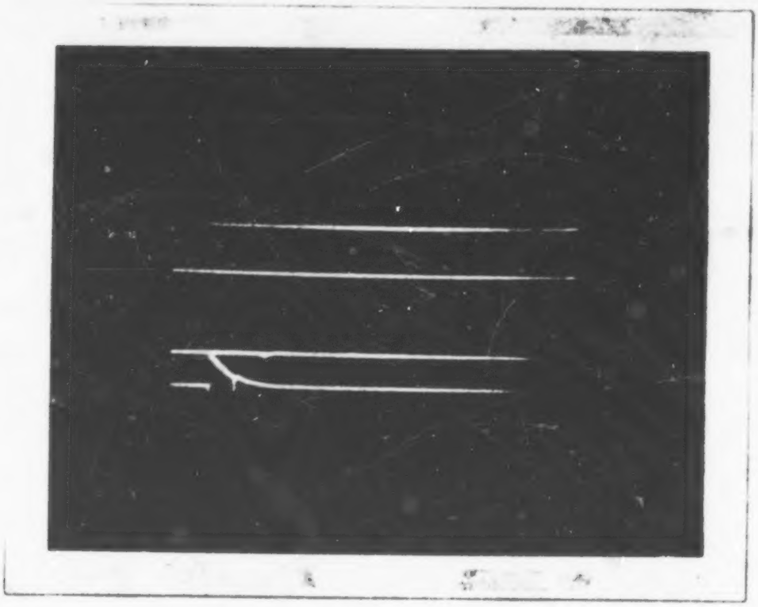
50ms/div
.1V/div

CONSTANT VOLUME DOWNWARD

75g/m³ cornstarch 3.9g → 1.95g/disp



50ms/div
.1V/div
10mV/div
60ms delay
$\Delta p|_{max} = 8.47$ psi
R.P. ~ 10psig
$\left(\overline{\frac{dp}{dt}}\right) = 83$ psi/s

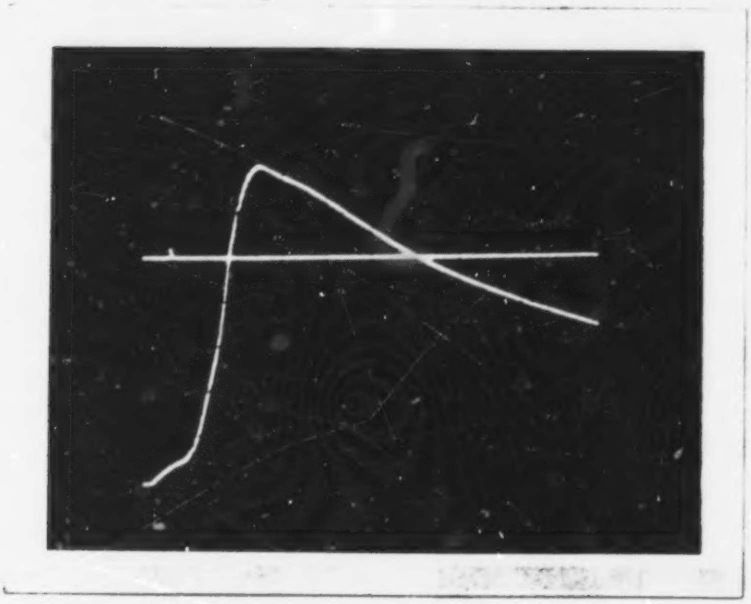


50ms/div
.1V/div

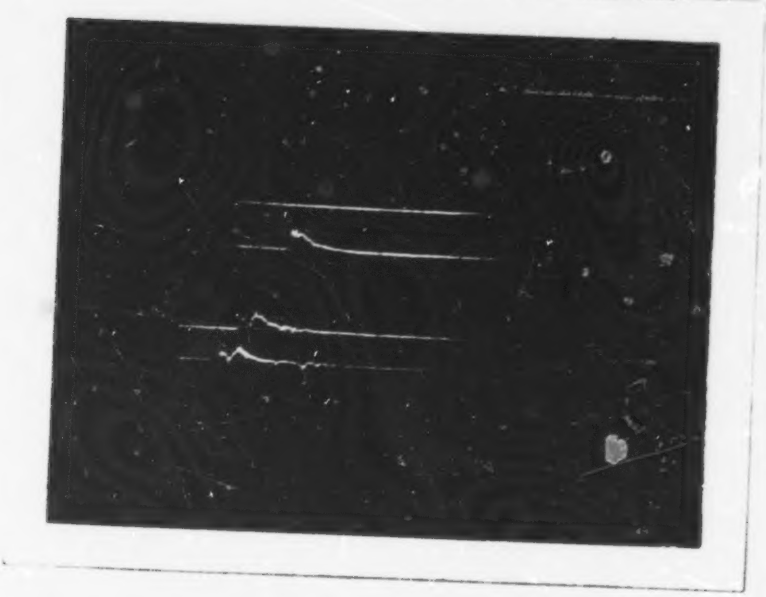
CONSTANT VOLUME DOWNWARD

150g/m³ cornstarch

X



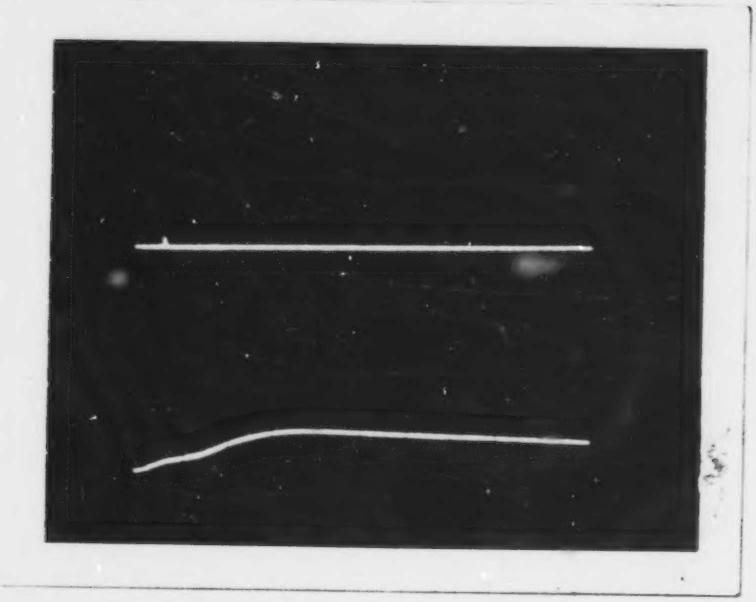
.1s/div
.1V/div
20mV/div
60ms delay
$\Delta p|_{max} = 26.9$ psi
P.P. ~
$\left(\frac{dp}{dt}\right) = 227$ psi/s



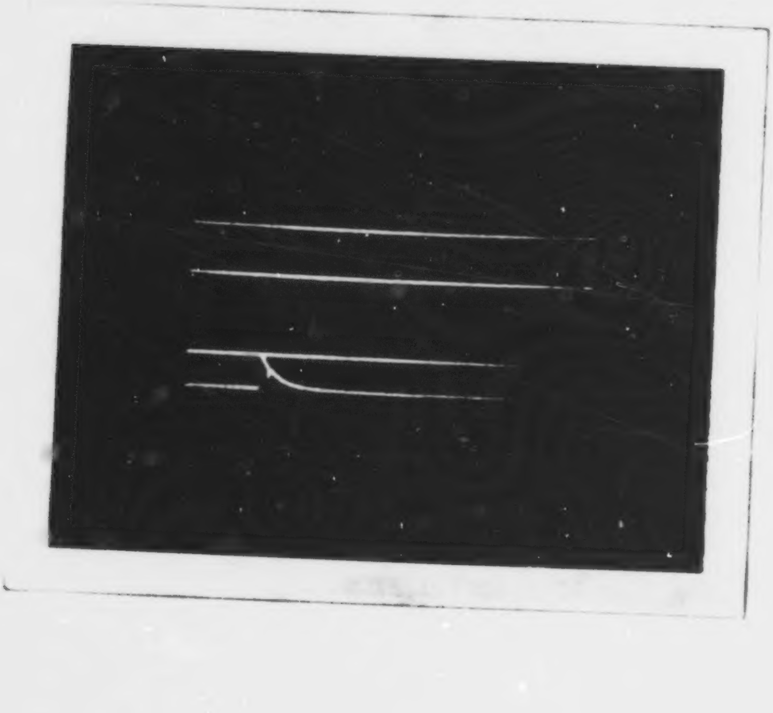
50ms/div
.1V/div

CONSTANT VOLUME DOWNWARD

150g/m³ cornstarch   7.8g ⇒ 3.9g/disp



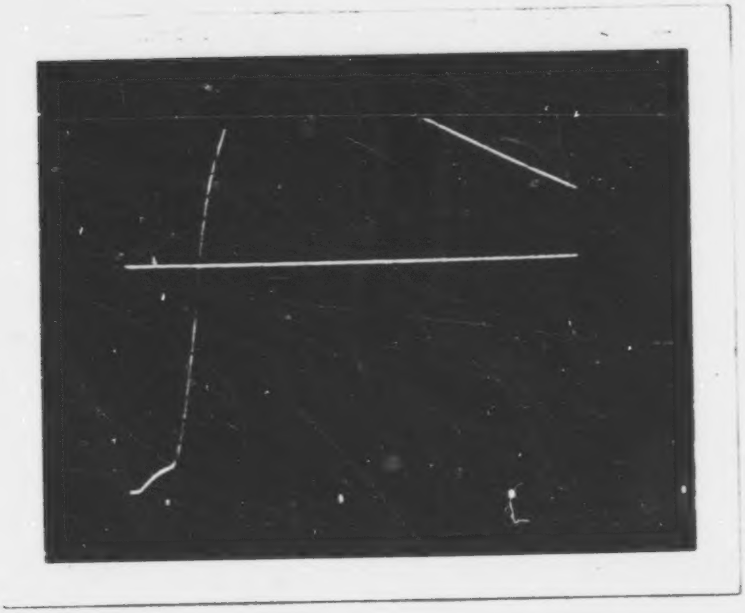
.1s/div
.1V/div
50mV/div
60ms delay
Δp|max = 6.7psi
R.P. 20psig



50ms/div
.1V/div

CONSTANT VOLUME DOWNWARD

175 g/cm^3 cornstarch 9.1 g ⇒ 4.55 g/div



.1 s/div

.1 V/div

20 mV/div

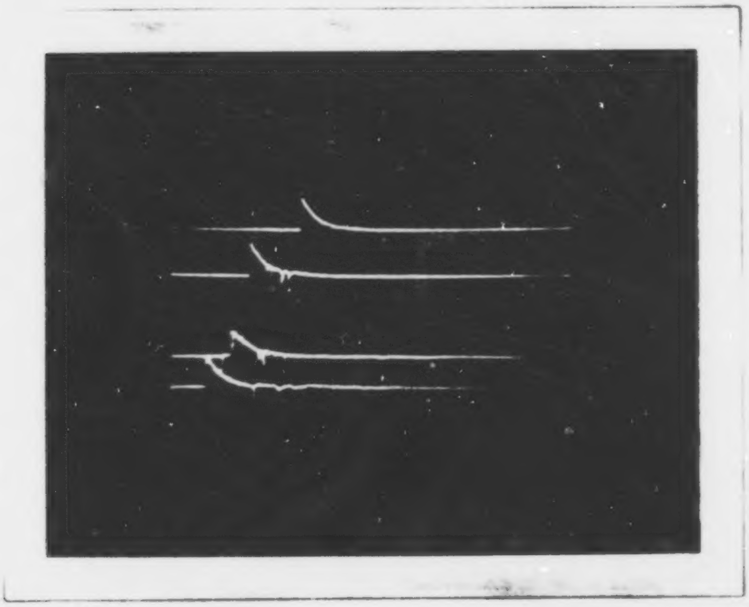
60 ms delay

$\Delta p|_{max} \simeq 36\text{-}37$ psi

P.P. = 135 psig

B C

$\left(\frac{dp}{dt}\right) = 250$ psi/s

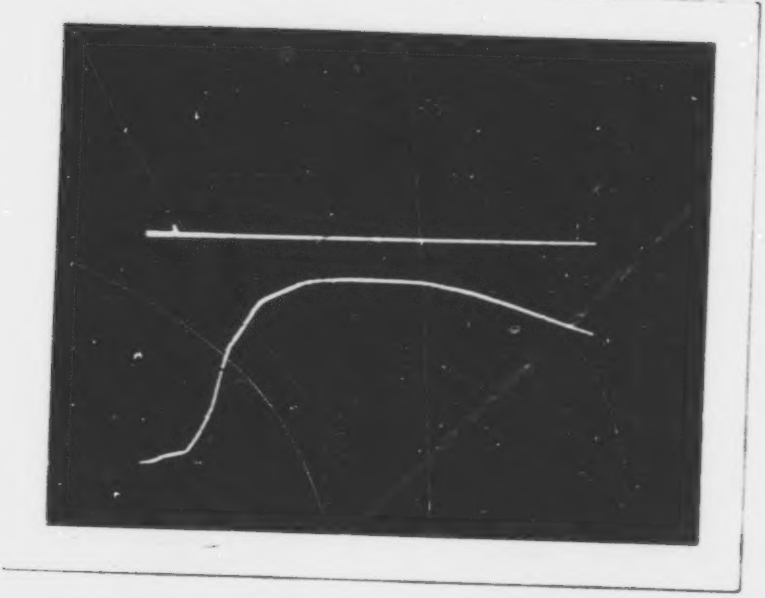


50 ms/div

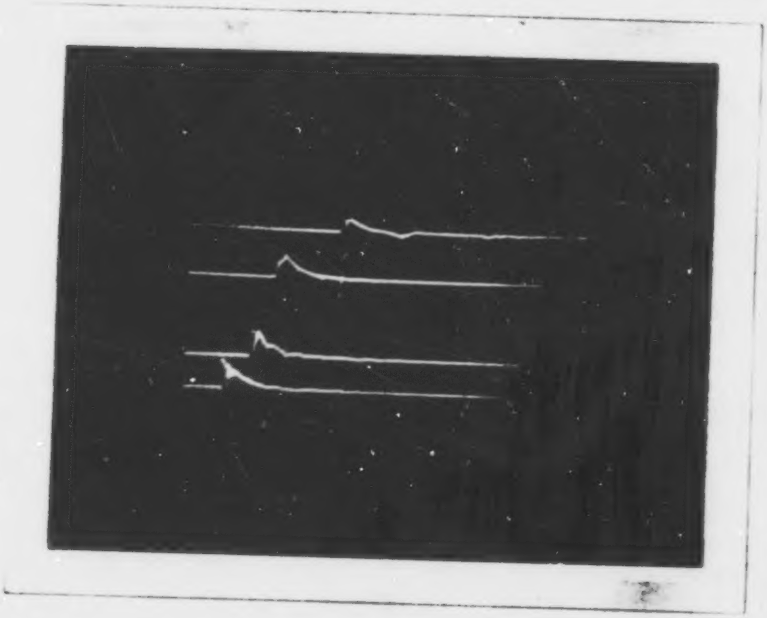
.1 V/div

CONSTANT VOLUME DOWNWARD

200g/cm^3 cornstarch 10.4g ⇒ 5.2g/disp



.1s/div
.1V/div
50mV/div
60ms delay
$\Delta p|_{max}$ = 41.3ps
$\left(\frac{dp}{dt}\right)$ = 205psi/

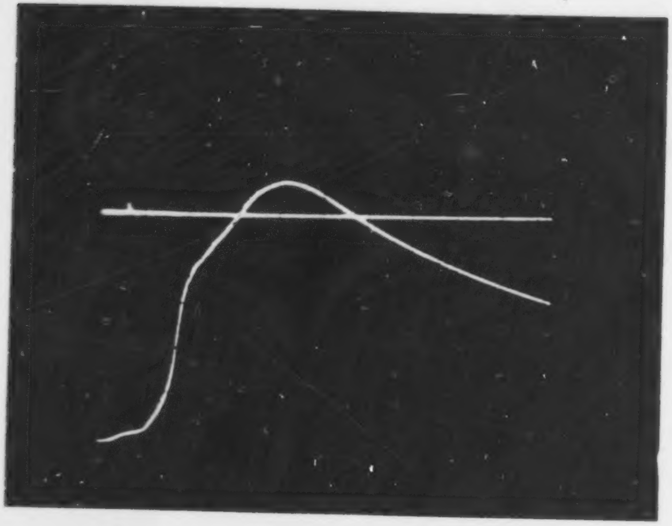


50ms/div
.1V/div

CONSTANT VOLUME DOWNWARD

275g/m³ cornstarch

14.3g ⇒ 7.1s/di



·1s/div

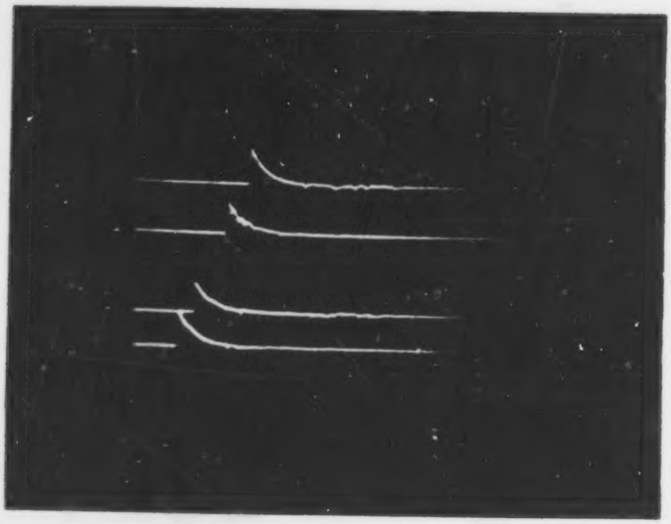
·1V/div

50mV/div

60ms dela

$\Delta p|_{max} = 58$

$\left(\frac{dp}{dt}\right| = 287$ ps

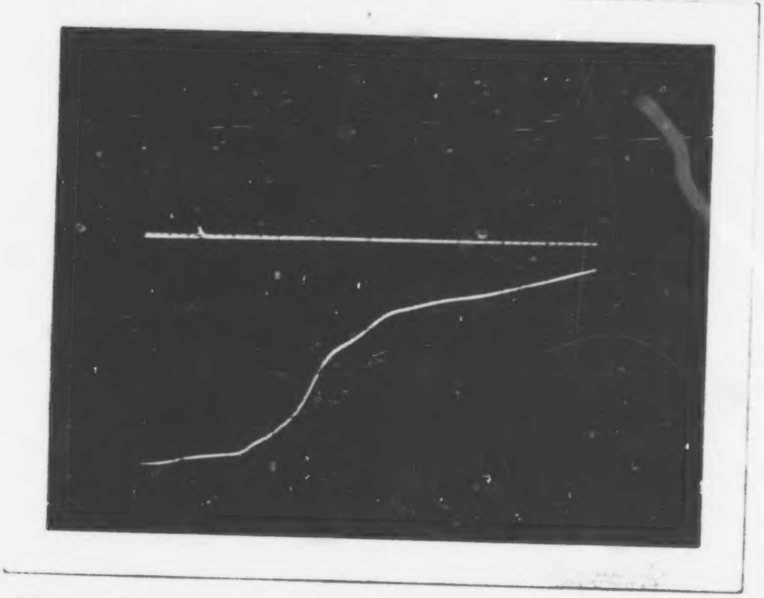


50ms/di

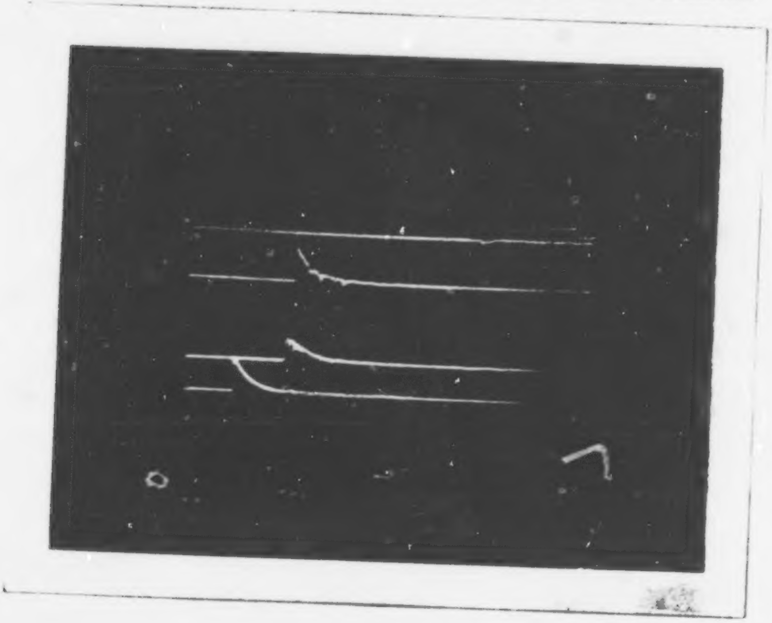
·1V/di

CONSTANT VOLUME DOWNWARD

300g/m³ cornstarch   15.6g ⇒ 7.8g/disp



50ms/div
.1V/div
50mV/div
60ms delay
Δp/max > 47psi



50ms/div
.1V/div

APPENDIX I

QUENCHING OF DUST-AIR FLAMES

by

J. Jarosinski, J.H. Lee, R. Knystautas and
J.D. Crowley

Proceedings of the 21st Symposium (International)
on Combustion, The Combustion Institute (1988).

Twenty-first Symposium (International) on Combustion/The Combustion Institute, 1986 pp. 1917–1924

QUENCHING OF DUST-AIR FLAMES

J. JAROSINSKI*, J.H. LEE, R. KNYSTAUTAS AND J.D. CROWLEY
Department of Mechanical Engineering
McGill University
Montreal, Canada

Flame quenching in mixtures of cornstarch, aluminum and coal dusts with air is studied in a vertical tube 0.190 m inside diameter and 1.8 m long with quenching plates held in the middle. The lean flammability limit determined under constant pressure conditions appears to be several times greater than that determined in constant volume for dust-air mixtures investigated. Quenching distance is measured for a flame propagating upward from the open to the closed end of the tube. The minimum quenching distances are 5.5 mm for cornstarch, 10.4 mm for aluminum, 25.0 mm for coal with fine particles (less than 5 μm), about 190 mm for coal with coarse particles (less than 70 μm), and 2.0 mm for stoichiometric methane-air mixture. Because the order of magnitude of the measured quenching distance in cornstarch and aluminum dust flames is the same as in gas flames, it is inferred that the processes controlling propagation in these flames should be similar. The large value of the quenching distance for coal dust-air mixture with coarse particles can be explained by the large particle size of the coal dust used in the experiments. Quenching distance can be used to identify the controlling processes in laminar premixed coal dust-air flames. Unlike burning velocity and minimum ignition energy which are apparatus dependent, quenching distance determined in limit quenching conditions should not be apparatus dependent.

Introduction

While research on dust combustion has been in progress for many years, the detailed mechanisms of the dust combustion process are still not fully understood. Insufficient knowledge of premixed laminar dust flame properties and the mechanism of their propagation inhibit the development of modeling of dust combustion processes as well as the development of theories. Detailed recent reviews of research into propagation of laminar premixed coal dust-air flames may be found in the work of Smoot et al. [1] and Krazinski et al. [2] Although past research and analysis has identified the general characteristics of laminar premixed coal dust-air flames, the details of the processes in the flame have not been resolved. Analysis by Slezak et al. in [3] shows that flame speeds have been reported from 3 to 200 cm/s, depending on the type of apparatus in which the investigation was conducted.

Measurements of minimum ignition energy in dust mixtures have been recently reported by Ballal [4,5] and Hertzberg et al. [6]. Ballal carried out experiments in dust clouds of carbon, graphite, coal, aluminum and magnesium. Energy requirements for the spark ignition in air of polyethylene powder, lycopodium, and Pittsburgh coal dust have been determined by Hertzberg et al. [6]. In this work the authors reported that the accurate determination of the minimum ignition energy of a dust involves extraordinary complications. The most important one is producing a quiescent dust-air mixture with reproducible concentration. They illustrated the complications with the minimum ignition energy for lycopodium which varies from 25 mJ to 50 mJ in data obtained by the Bureau of Mines compared with a value of about 10 mJ determined by Eckhoff [7].

Recently, using a model systematically developed since 1976 [8], Smoot and co-workers [9] reported a series of parametric predictions to identify the controlling processes in premixed fine coal dust-air flame. It has been found, as a result of this prediction, that the rate of flame propagation is controlled by the rate of streamwise molecular diffusion of oxygen and volatiles, together with heat conduction from the

---

*Permanent address: Institute of Aeronautics, Al. Krakowska 110/114, 02–256 Warszawa, Poland

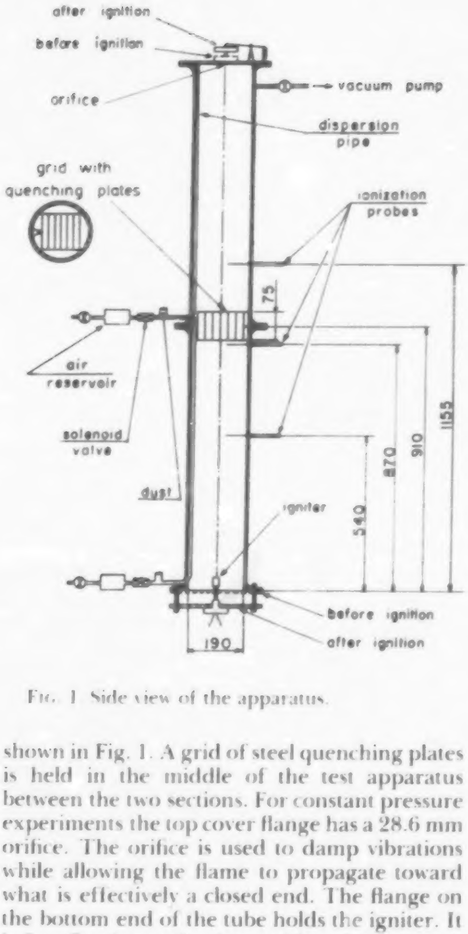


FIG. 1 Side view of the apparatus.

hot gas to the particles. It also has been found that radiation, heterogeneous reaction, the rates of coal devolatilization, and volatile oxidation in the gas phase play a secondary role in the propagation of analyzed flames.

Opinions diverge on the processes controlling flame propagation indicating that the mechanism of flame propagation in premixed laminar dust-air mixtures is not clearly understood. The calculated results based on the model of Slezak et al. [10] consider are different from those of Smoot et al. [9]. Smoot considers radiation unimportant in the mechanism of flame propagation and reports that the thickness of premixed laminar coal-dust flame is in the range of 0.5–4.0 cm. Slezak et al [3,10] consider radiation important in the mechanism of flame propagation and report that the thickness of a premixed laminar coal dust flame is very large compared to a gas flame and may even approach one meter in thickness. In contrast, Smoot and Ballal accept conduction and molecular diffusion as the controlling processes of flame propagation in dust-air mixtures but differ in quantifying the role of heterogeneous reaction and gas phase chemical reaction of volatiles in coal dust flames [5,9].

More reliable experimental data are required to verify the mechanism of flame propagation in laminar premixed dust-air mixtures. Burning velocity and minimum ignition energy are not sufficiently fundamental because they are apparatus dependent. It is also important to know the quenching distance but there does not appear to be any published data on the quenching distance of freely propagating dust-air flames[a]. For gas mixtures the quenching distance is closely related to flame thickness. If the order of magnitude of measured quenching distance in dust flames is the same as for gas flames, the processes controlling dust-flame propagation should be similar to those of gas flames. Therefore, measuring the quenching distance can provide valuable insight into the mechanism of flame propagation in dust-air mixtures.

Experimental Details

All experimental work was carried out in a vertical steel tube, 0.190 m inside diameter and 1.880 m long (volume = 53.3 L). The apparatus consists of two sections bolted together as shown in Fig. 1. A grid of steel quenching plates is held in the middle of the test apparatus between the two sections. For constant pressure experiments the top cover flange has a 28.6 mm orifice. The orifice is used to damp vibrations while allowing the flame to propagate toward what is effectively a closed end. The flange on the bottom end of the tube holds the igniter. It is free-floating so that it can either close or open the bottom of the tube.

Before an experiment the vessel is first evacuated to 150 torr below atmospheric pressure. The experiment begins with the opening of a solenoid valve causing the dispersion of the dust by an air blast from a 0.23 L compressed air reservoir. The air passes through the dust reservoir where it entrains the dust which is then dispersed by a perforated tube located inside the test vessel. The duration of the dispersion process is less than 100 ms and the mixture introduced causes the pressure to increase. Ignition with a 1.2 gram black powder match with a calorimetric energy of 12 J follows the beginning of dispersion by 200 msec. The pressure at ignition is slightly less than 0.1 MPa absolute. The increasing pressure releases the cap at the top end of the tube and the cover-flange at the bottom end of the tube.

---

[a] One of the reviewers kindly pointed out some measurements of quenching distance for Pittsburgh coal in two unpublished reports showing values of 7–10 mm, but it is not known if the data were determined for freely propagating flames.

Once the tube is open the pressure remains constant, the combustion products vent to the atmosphere and the flame propagates upward freely. After each test the dispersion system is purged of any residue and the tube is opened and swept clean.

The time delay between dispersion and ignition is controlled by a mechanical timer which permits time delays of up to 250 ms. Two limit switches control the opening and closing of the solenoid valves, and one limit switch controls the time of ignition.

The flame arrival is detected at the axis of the test vessel by three ionization probes biased at a 400 VDC potential and their signal is recorded on an oscilloscope.

The quenching distance of the flame is measured by varying the composition of the fuel-air mixture until the limit concentration is found for a particular gap. The quenching plates measure 1.5 mm × 75 mm × 130 mm and are arranged to form a 130 mm square grid with the 75 mm edge parallel to the axis of the tube. The quenching distance is adjusted by varying the size of the spacers placed between the quenching plates. The number of plates used varies with the size of the spacers.

The gaseous fuel-air mixture is made by blending air and gas with calibrated rotameter-type flow meters. To ensure that the mixture is homogeneous, a volume of mixture three times the volume of the test vessel is flushed through prior to ignition. The solid fuels used are cornstarch, aluminum and coal dusts. The mean dust-air mixture composition is varied by changing the mass of dust placed in the dispersion vessel. Distribution of dust along and across the tube are controlled during its dispersion by the calibration of the dispersion system. The formation of the dust-air cloud is a transient process - after dispersion the concentration changes along the tube. To ensure that there is dust-air mixture between the quenching plates the initial air pressure of the lower dispersion system is 25–35% greater than that of the upper system. Typical dispersion pressures are 1.03 MPa upper and 1.37 MPa lower (gauge). Upon dispersion, air and dust sweep through the plates as the pressure in the vessel goes to equilibrium. For these conditions high reproducibility of data from experiment to experiment for different concentrations is obtained. The procedure permits a reproducible mixture composition in the region of the quenching plates and makes it possible to properly determine the minimum quenching distance. However the mean concentration at which the minimum quenching distance is determined may not be the absolute concentration - as in other experiments, this quantity may be apparatus dependent. Turbulence due to dispersion is assumed not to affect the flame because its decay time is of the order of 200 ms compared to about 1.0 s required for the flame to reach the quenching plates.

Cornstarch ($C_6H_{10}O_5$) consists mostly of volatiles with little fixed carbon or ash. The particles are nearly spherical in shape and are fairly uniform in size with a mass mean diameter of 15 μm. The method of preparing the cornstarch fuel adopted for the present investigation consists of mixing the cornstarch with 1% by mass of fumed silica gel and storing it in an open jar in an oven at 40°C.

Aluminum dust consists of either aluminum flakes with an average particle size of 15 μm × 0.1 μm or atomized aluminum particles with average diameter of 7.5–9.5 μm (Fischer).

The bituminous coal dust (DEVCO No. 26) used consists of a sample passed through a 200 mesh (70 μm) screen and contains a broad distribution of particle sizes. Its properties in comparison with the standard Pittsburgh bituminous coal dust as determined by the CANMET laboratory are presented in Table I. To reveal the influence of particle size on the quenching distance the same coal was ground and particles less than 5 μ m were selected. A proximate analysis of the ground coal dust shows the same characteristics as in Table I.

Results

Since the quenching distance of freely propagating gas flames is well documented the vessel was calibrated with methane-air flames in constant pressure conditions with the bottom end of the tube open and the flame propagating toward the closed end. Under these conditions the propagation velocity of the flame front is effectively controlled by the velocity of the ascending buoyant gases rather than by the relatively small burning velocity of the mixture. The surface of the flame adjusts itself to the velocity of the leading point and to the laminar burning velocity in such a manner that $S u_l = F u$, where S is the flame area, F the cross-sectional area of the tube, u_l the laminar burning velocity and u flame speed [12].

Tests of the apparatus indicate the quenching behaviour of upward freely propagating methane-air flames to be typically U-shaped as expected. As shown in Fig. 2, the results are similar to those obtained earlier in a 50 mm square tube [13] and are in agreement with the data of Lewis and Elbe [18]. Since the scales of these apparatus are different it is concluded that

TABLE I
Properties of Coal Dust Samples [12]

Source	Proximate Analysis % Moisture	Ash	V.M.	F.C.	Specific Surface Area cm^2/g	Minimum Explosive Concentration (Hartmann Apparatus) g/m^3
DEVCO NO. 26	0.70	4.47	32.09	62.74	2190	67
PITTSBURGH (Std.)	1.44	4.91	37.52	56.23	2670	70

for a gas mixture the minimum quenching distance is not apparatus dependent. Themum quenching distance for methane-air is 2.0 mm and occurs at the stoichiometric mixture. Differences at the limit concentration are attributed to the difference in the scale of the experiments.

It was found that the lean flammability limit of cornstarch-air mixture is different when determined at constant volume as compared to constant pressure. In the constant volume cylindrical bomb (0.18 m^3) this limit was found to be 70 gm/m^3 [14], while in constant pressure experiments in the present work it was about 380 g/m^3. Lean limit dust concentration at constant pressure conditions was considered the leanest dust concentration at which a flame was observed to propagate the entire length of the tube. Tests made with the apparatus under constant volume conditions indicate that cornstarch-air flames propagate easily and have substantial pressure rise with a concentration as low as 200 g/m^3, well below the constant pressure lean limit of 380 g/m^3. Thus the series of experiments made in the same apparatus, but in the different conditions of constant volume and constant pressure, confirm the existence of two different lean flammability limits.

The quenching distance as a function of the cornstarch dust-air mixture concentration is shown in Fig. 3. The graph shows two distinct regions for the sensitivity of the flame quenching distance to dust concentration. For concentrations less than 500 g/m^3, a small change in dust concentration results in a large change in quenching distance. At 500 g/m^3 there is an abrupt change in the slope of the graph followed by a second region less sensitive to a change in dust concentration. The minimum quenching distance for cornstarch-air mixture is 5.5 mm at a dust concentration of 800 g/m^3 which is 3.4 times the theoretical stoichiometric mixture. To the right of this point the graph exhibits a rising trend - behavior which is characteristic of a rich limit.

Figure 4 presents the experimental results of the quenching distance of aluminum. The lean flammability limits for flames propagating freely through aluminum dust-air mixtures in constant pressure conditions are 415 and 435 g/m^3 for flake and atomized particles respectively. These are approximately 3.0 times the lean limit in Ballal's experiments [5] and approximately 1.4 times the stoichiometric composition. The quenching diameter for this kind of dust is reported by Ballal to be of the order

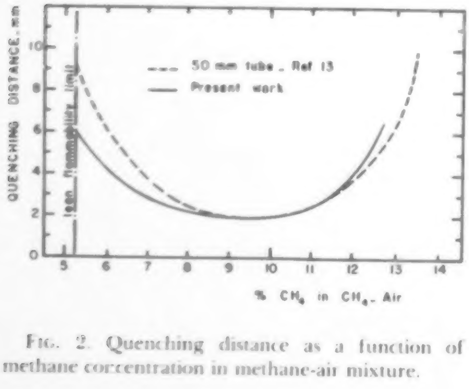


FIG. 2. Quenching distance as a function of methane concentration in methane-air mixture.

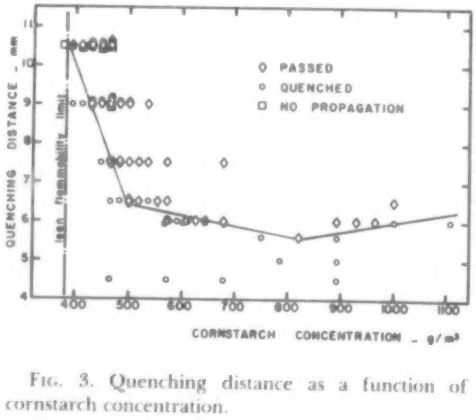


FIG. 3. Quenching distance as a function of cornstarch concentration.

of 4.0 mm. However, investigation shows that the minimum quenching distance for a freely propagating flame in an aluminum dust-air mixture is 10.4 mm at a dust concentration of 850 g/m^3, which is 2.8 times the theoretical stoichiometric mixture. Aluminum also demonstrates behavior consistent with a rich limit.

In experiments with coal dust-air mixtures in which coarse coal dust was used, unexpected behaviour of the flame has been observed. In spite of repeated attempts to obtain freely propagating flames through the mixture, the flame failed to propagate regardless of mixture concentration. Increasing the content of volatile matter by the addition of 5% by mass of cornstarch to the coal dust made it possible for the flame to propagate. Propagation was observed for coal dust concentrations ranging from 500 g/m^3 to 1100 g/m^3. The flame could pass the entire length of the tube only in the absence of any quenching plates between the two sections of the tube. It is evident from these results that the 19.0 cm tube diameter was very close to the quenching diameter for the coal dust-air mixture investigated. The results of experiments conducted with fine coal particles are shown in Fig. 5. The lean flammability limit is 280 g/m^3 and the minimum quenching distance 25 mm at a dust concentration of 590 g/m^3 which is 4.7 times the theoretical stoichiometric mixture.

Discussion

Lean limits determined in constant pressure conditions appear to be several times greater than those determined in constant volume for all the dust-air mixtures investigated. One possible explanation is that below the lean limit concentration the burning velocity is too low to form a self-propagating flame. It is known for different combustion gases in mixtures with air that the limit burning velocities are about 3 cm/s for ammonia, 5 cm/s for methane, and 7 cm/s for propane. The limit burning velocities for dust mixtures are not known, but should be of the same order of magnitude. The difference in lean limit concentration at constant volume and constant pressure could be explained by the observation that when a flame is pushed by hot gases it can propagate with a lower burning velocity [15].

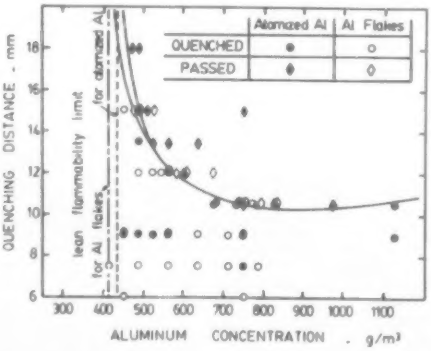


FIG. 4. Quenching distance as a function of aluminum flake concentration.

Results of experiments show that the quenching distances of cornstarch-air and aluminum-air mixtures are comparable to the quenching distances of gas flames. For methane-air mixture, for example, the quenching distance is equal to 2.0 mm for stoichiometric mixtures, 9.2 mm for the lean limit mixture, and even more for the rich limit, so it is in the same range as the dust-air flames investigated.

Because the quenching distances of flames propagating in cornstarch-air and aluminum-air are comparable with quenching distances of methane-air mixtures, the processes controlling flame propagation in these mixtures should be similar, though these two dust mixtures have very different physical properties. In both dust-air flames heat conduction from the high temperature combustion zone raises the particle temperature to start volatilization or vaporization. The flame propagation is controlled in this case by heat conduction from the hot gas to the particles and by the rate of streamwise molecular diffusion of oxygen and volatiles or aluminum vapour.

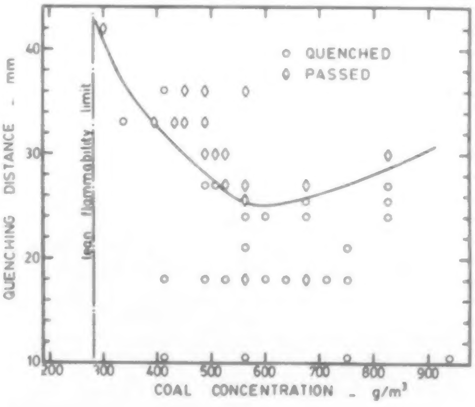


FIG. 5. Quenching distance as a function of fine coal concentration for particles less than 5 μm in diameter.

It is known for flames propagating in gas mixtures that the quenching distance is twice the flame thickness [13]. From the point of view of similarity of processes in the flames under consideration, the same relation should be valid for both gas and dust-air flames. It follows from this that the flame thickness which corresponds to the minimum value of quenching distance for cornstarch with air is approximately 2.8 mm and for aluminum with air it is approximately 5.2 mm.

It is shown in [16] that for real flames the relation between the flame thickness δ_L (as defined in [17]) and the characteristic thickness $\Delta = \gamma / C_p \rho_u u_L$ is $\delta_L \simeq 8\,\Delta$, where λ is the thermal conductivity, C_p the specific heat at constant pressure, ρ_u the density of unburned mixture and u_L the burning velocity, with λ/C_p calculated at the mean value of the temperature range across the flame front. This relation makes it possible to estimate the burning velocity at the quenching conditions. For the cornstarch air mixture $u_L \simeq 14.5$ cm/s and for aluminum-air mixture $u_L \simeq 11$ cm/s (λ / C_p calculations were based on the properties of air).

Experimental results of aluminum dust-air flames can be compared with those of Ballal [4,5] only on a limited scale. The range of concentrations reported by Ballal is 140 to 330 g/m^3, while results reported in this paper are for concentrations ranging from 415 g/m^3 (lean flammability limit for freely propagating flame in apparatus used in experiments) to 1100 g/m^3. The quenching distance determined by Ballal [5] is the minimum diameter which develops the flame initiated by a spark with near-limit ignition energy. The quenching distance measured in the present work is the maximum spacing between the walls for which heat outflow to the walls is able to quench the fully developed freely propagating flame. For a gas mixture the quenching distance and minimum flame diameter are almost equal [18]. From this point of view the minimum flame diameter for methane-air mixture determined by Ballal and cited in [5] is surprisingly small and disagrees with the measurements of Lewis and Elbe [18] ($\simeq 0.6$ mm compared to more than 2.0 mm respectively). The minimum quenching distance as determined in the present study for the aluminum dust-air flame appears to be 10.4 mm compared to a quenching diameter of 4 mm reported by Ballal [5]. Because the quenching diameter for the methane-air mixture reported by Ballal is also less than that which is commonly accepted, one must conclude that the method used by Ballal lowers the value of the quenching diameter.

For coal dust-air mixtures in which coarse coal dust was used, the quenching distance appears to be unexpectedly large, which can be explained by the relatively large particle sizes used in the experiments. There is some agreement of data in the present work with that reported by Slezak et al. [3]. The distribution of particle sizes in both dusts was similar. The lean flammability limit with the added 5% of cornstarch dust was practically the same as in [3]. The behaviour of the flame during its propagation along the tube was also similar. However, the interpretation of the results is different. In the present work the difficulty with flame propagation inside the tube may be due to a low burning velocity which is below the limit burning velocity. In the paper of Slezak et al. [3], the burning velocity is very high, much higher than usually estimated. The method used to determine its value is doubtful. According to Zeldovich this kind of flame propagation is highly influenced by buoyancy which determines the velocity of the leading point of the flame [12]. The surface of the flame adjusts itself to both the velocity of the leading point and the laminar burning velocity. Accuracy in calculating the burning velocity depends on the accuracy in determining the flame surface. The authors used a two-dimensional parabola to measure the surface of the flame front, which as they observed themselves was "bushy" and three-dimensional. As a result the measured burning velocity appears very high. Also, their temperature records show that the burning velocity cannot be high since the temperatures appear to be close to the limit temperature.

The results of experiments conducted with 5 μm coal show the minimum quenching distance to be larger than expected. Though the mass mean diameter of coal particles used was much smaller than that of cornstarch and smaller than that of atomized aluminum, the quenching distance appears to be several times larger than for cornstarch and aluminum dust-air flames and by an order of magnitude higher than for methane-air flames. The difference is probably due to the relatively small content of volatile matter in coal dust.

Conclusions

Quenching distance has been measured in a relatively large scale apparatus for freely propagating flames in dust-air mixtures of cornstarch, aluminum and coal. Minimum quenching distances for cornstarch and aluminum dust with air are 5.5 mm and 10.4 mm respectively. These values are comparable with experimental data for gas flames. Because the order of magnitude of quenching distance measured in cornstarch and aluminum dust flames is the same as in gas flames, the processes controlling flame propagation in these flames should be similar.

Quenching distance in coal dust-air mixtures with coarse coal (particles less than 200 mesh) containing a broad distribution of particle sizes was indirectly inferred to be 190 mm while in mixtures with fine coal (particles less than 5 μm) its value was 25 mm. The large value of quenching distance in the first case can be explained by the particle size and low volatile content of the coal. Increasing particle size increases the flame thickness and decreases the burning velocity (i.e., increases the quenching distance). The relatively large quenching distance for fine coal dust may be the result of the relatively small content of volatile matter.

The experimental study of the present paper offers the quenching distance as the most fundamental quantity which can be used to identify the controlling processes in dust combustion. Such quantities as burning velocity, flame thickness, and minimum ignition energy depend on the apparatus and are thereby not sufficiently fundamental. Quenching distance, linked directly with flame thickness, determined by definition in limit quenching conditions, if properly measured, should not be dependent on the apparatus.

Acknowledgements

This work was supported by the Natural Sciences and Engineering Research Council of Canada under NSERC Grants A7091 and A3347 and by Energy, Mines and Resources of Canada under Contract OST 85-00119.

REFERENCES

1. Smoot, L.D. and Horton, M.D.: Prog. Energy, Combust. Sci., 3: 235–258, 1977.
2. Krazinski, J.L., Buckius, R.O. and Krier, H.: Prog. Energy Combust. Sci., 5: 31–71, 1979.
3. Slezak, S.E., Fitch, D.J., Krier, H., Buckius, R.O.: Combustion and Flame, 54: 103–119, 1983.
4. Ballal, D.R.: Proc. R. Soc. London, A369: 479–500, 1980.
5. Ballal, D.R.: Proc. R. Soc. London, A385: 1–19, 1983.
6. Hertzberg, M., Conti, R.S., Cashdollar, K.L.: Twentieth Symposium (International) on Combustion, pp. 1681–1990, 1984.
7. Eckhoff, R.K., Combustion and Flame, 24: 53–64, 1975.
8. Smoot, L.D., Hecker, W.C. and Williams, G.A., Combustion and Flame, 26: 323–342, 1976.
9. Smoot, L.D., Hedman, P.O. and Smith, P.J.: Prog. Energy Combust. Sci., 10: 359–441, 1984.
10. Slezak, S.E., Buckius, R.O. and Krier, H.: Combustion and Flame, 59: 251–265, 1985.
11. Feng, K.K.: "Hazardous Characteristics of Canadian Coal Dust". Canada Centre for Mineral and Energy Technology, Division Report ERP/MRL 82–132 (OP) (J), 1982.
12. Zeldovich, Ya.B.: Combustion and Flame, 40: 225–234, 1981.
13. Jarosinski, J.: Combustion and Flame, 50: 167–175, 1983.
14. Gaug, M., Knystautas, R., Lee, J.H.S., Nelson, L, Benedick, W.B. and Shepherd, J.: Dynamics of Reactive Systems Part II: Modeling and Heterogeneous Combustion, Progress in Astronautics and Aeronautics Vol 105, pp. 155–168 (1986).
15. Jarosinski, J., Strehlow, R.A., and Azarbarzin, A.: Nineteenth Symposium (International) on Combustion, pp. 1549–1557, 1982.
16. Jarosinski, J., Combustion and Flame, 56: 337–342, 1984.
17. Andrews, G.E. and Bradley, D., Combustion and Flame, 19: 275–288, 1972.
18. Lewis, B. and von Elbe, G.: Combustion, Flame and Explosion of Gases, New York, Academic Press, 1964.

COMMENTS

G. Continillo, C.N.R. Please explain how you could reach substantive conclusions about the dominant mechanism of flame propagation from your measurements of quenching distance. In other words, what would you expect to observe if the dominant mechanism was heterogeneous combustion at the surface?

Author's Reply. The quenching distance is related to the flame thickness where the flame thickness is typically half the quenching distance. If the quenching distance for the dust flame is as small as our current measurements indicate, this implies that the flame is thin. This in turn suggests that the mechanism of flame propagation is controlled by the thermal diffusion process.

●

C. Lawn, C.E.G.B. Marchwood. As I remember

Ballal's system, he defined his quenching distance in terms of the distance between two point electrodes which just failed to produce ignition when a spark was passed between them. Isn't it rather unlikely that this definition will yield results which agree quantitively with the one you are adopting?

Author's Reply. It is true that Ballal's work predominantly addresses the measurement of the minimum ignition energy in carbon and three metallic dusts. The initiation spark discharge is between two flanged electrodes. It is well known that in gas phase reactions ignition and quenching are intimately related. Failure to initiate can be interpreted as failure to maintain propagation within the confining boundaries. Ballal himself infers this by the empirical relation between the quenching distance d_q and the optimum spark gap width d_g, viz. $d_q = 0.8\ d_g$.

●

M. Sichel, Univ. of Michigan. Two critical quenching lengths have been described in your paper and the subsequent discussion. One length, the one you measured, is the minimum plate separation which still permits flame passage. The second is the minimum tube diameter which will permit initiation and flame propagation. Would you expect these two lengths to be the same in the case of dust flames?

Author's Reply. The underlying mechanism for both situations you mention is the same, namely the balance of the rate of heat loss to the walls and the rate of energy release in the reaction zone. The geometric difference should be of minimal importance.

●

C. W. Kauffman, Univ. of Michigan. For the propagation of a layered dust cornstarch flame under constant pressure conditions we find a lean limit of approximately 200 g/m^3 layered or 100 g/m^3 suspended. This is significantly lower than your result. Can you speculate as to why you measure such a high lower explosion limit?

Author's Reply. The layered dust flames to which you refer, to the best of my knowledge, involve strong convective motion of the dust suspension ahead of the flame. In our case, the dust suspension is in a relatively quiescent state and this can account for the differences observed.

APPENDIX II

INFLUENCE OF TURBULENCE ON CLOSED VOLUME EXPLOSION OF DUST-AIR MIXTURES

by

J.H.S. Lee, Y.K. Pu and R. Knystautas

Archivum Combustionis, Vol. 7 (1988)

archivum
combustionis
Vol 7 (1987) No 3/4

Influence of Turbulence on Closed Volume Explosion of Dust-air Mixtures

J. H. S. LEE, YI-KANG PU and R. KNYSTAUTAS

Dept of Mechanical Engineering McGill University
Montreal, Canada

The majority of experiments on dust explosion are carried out in closed chambers
of various geometrical shapes and sizes. Different methods of dust dispersion are also 998
used Turbulence is thus an intrinsic property of a dust-air mixture and since turbulence
depends strongly on boundary conditions, the turbulence characteristics vary widely
between different experimental apparatus. In almost all the closed bomb experiments,
the standard and quite often the sole diagnostic use is the pressure-time development
of the explosion process. From the $p(t)$ curve the two pieces of information that USED
can be derived are the Δp_{max} which signifies the energetics of the process and $(dp/dt)_{max}$ ^
which characterizes the burning rate. To enable comparisons to be made between
different apparatus, the $(dp/dt)_{max}$ is scaled with the cube root of the volume of the
vessel to form the K_{ST} factor. A lot of data seems to support the so called cubic SO-CALLED
law, ie, K_{ST} = constant for a given dust mixture. However, it was shown also that 999 SEEM
^

Zam 583 Arch Comb. A.W. str 48

szp. 17

turbulence can cause significant departure from the cubi law. Some data also suggest
NOT an almost linear correlation between K_{ST} and Δp_{max}. However, such a correlation is CUBIC
^ not universal. The theoretical basis for the cubic law is in essence the classical theory ^
for constant volume flame propagation. However, its validity for dust explostion has
nor been explored fully, for has the relationship between K_{ST} and Δp_{max} been analyzed. EXPLOSION
NOR The purpose of this paper is to discuss the validity of the cubic law, the correlation X
X between K_{ST} and Δp_{max} and ^ explain possible physical processes that cause deviation 993
from classical theory. Experimental results from a scaled-up Hartmann bomb in which
the turbulence level can be varied are presented and discussed within the framework
TO of the $K_{ST} - \Delta p_{max}$ relationship.
^

1. Introduction

C It is well known that a fine dust-air mixture can support selfsustained flame propagation and even detonation waves under the appropriate conditions. However, unlike homogeneous gas-air mixtures, the fundamental explosion parameters ie. burning velocity, flammability limits, ignition energy, etc.) for dust mixtures are not well established. The underlying eason has to o with the dominant role played by turbulence, which not only controls the initial dispersion, hence the distribution of the dust and the uniformity of the dust cloud, but also the subsequent burning rate of the combustion processes. Since turbulence depends strongly on initial and boundary conditions, it is understandable that the explosion parameters are dependent on the dispersion technique, and the size and geometry of the apparatus used. Although it is possible to determine a unique burning rate of a particular dust for a standard apparatus and operational procedure, this burning rate does not have any special significance from a fundamental point of view. Nevertheless, it can serve as a relative measure of the combustion rate (on sensitivity) of different dusts if the same apparatus and procedure are used. The standard apparatus usually used to study dust explosion is the constant volume bumb of spherical or low L/D ratio cylindrical geometry. Burners and flame tubes are not convenient because of the large diameter required. For the most part, the standard diagnostic used in constant volume bomb explosion studies is the pressure-time history of the combustion processes. From the $p(t)$ curve one can deduce two parameters: Δp_{max} which is related to the energetics of the mixture and $(dp/dt)_{max}$ which is proportional to the burning rate. It is tempting t use gas dynamic theory for constant volume dust explosions and deduce a burning velocity from the $p)t($ curve obtained. However, without any knowledge of the structure of the dust flame and its thickness, the burning velocity derived from such a theory may not represent any real burning velocity. Thus it seems advisible at this stage to avoid the use of a theory together with its inherent assumptions in the analysis of the experimental data.

SELF SUSTA
^
SPACE
(
^
REASON
^
do
^
OR
BOMB
TO
^
p(t)
ADVISABLE

From the maximum rate of pressure rise, a useful parameter called the K_{ST} factor can be obtained (ie. $K_{ST} = V^{1/3}(dp/dt)_{max}$). The K_{ST} factor is in essence a scalled $(dp/dt)_{max}$ based on the volume V of the vessel used. Such scaling permits the $(dp/dt)_{max}$ from different sizes of explosion chambers to be compared. The work of Bartknecht [1] suggests that K_{ST} = constsnt (the so-called cubic law) for a given dust. Other investigators [2] question the general validity of the cubic law. There is some experimental evidence to indicate a linear dependence between K_{ST} and Δp_{max}. If there exists a correlation between K_{ST} and Δp_{max} then experimental data for different dusts, different apparatus, turbulence levels, etc., can be put in a common framework for comparison. On this basis, it would, therefore, seem worthwhile to investigate further the relationship between he K_{ST} factor and Δp_{max}.

SCALED
CONSTA.
THE

The objective of this paper is to explore the fundamental basis of the $K_{ST} - \Delta p_{max}$ relationship. From simple classical theory of constant volume combustion, a $K_{ST} - \Delta p_{max}$ relationship can be obtained. Using this idealized theoretical results as a reference, experimental data can be compared against such a reference. Agreement or deviation from this idealized theory may possibly shed light on the combustion processes involved. The experiments were carried out in an approximately four-fold scaled-up version of the classical Hartmann bomb. The coice of such a flame tube instead of a spherical bomb or a small L/D ratio apparatus (ie. $L/D \simeq 1$) was to anticipate future experiments in which the bomb would be extended to longer lengths such thet "one-dimensional" flame propagation could be studied.

CHOICE
THAT

2. Experimental Details

The explosion tube used in the present study was 190 mm in diameter and 910 mm long (Fig. 1). The ends of the tube were closed by blind flages. FLANGES

Zam. 583. Arch. Comb. A.W. str. 51 szp. 18

The method of dust dispersion was essentially a linear version of the circular perforated tube used by Bartknecht [1] in his standard 20 liter sphere or the 1 m^3 vessel. The linear dispersion tube in the present apparatus was 14 mm in diameter and 910 mm long running along one side of the inner wall of the explosion tube. Holes of diameter ranging from 1 mm to 2 mm were drilled along the entire length of the dispersion tube. The dispersion tube was connected to a small dust chamber (10 cm^3 volume) then via a solenoid valve to a high pressure air reservoir (230 cm^3 capacity). The air reservoir was pressurized to an overpressure ranging from 10 to 25 bars. When the solenoid valve was activated, the dust was convected along with the air flow and the dust-air mixture was discharged into the explosion tube through the linear array of holes. To suppress the directed momentum of the disperion jets, a circular rod 0.95 mm diameter was placed cm 4 mm away from the holes running parallel along the length of the dispersion tube. The rod provides an obstacle to break the jet momentum, preventing the dust-air jet from impacting on the opposite wall. Also, a deflected linear jet entrains and disperses more effectively resulting in a more uniform distribution of dust inside the explosion tube. To further optimize the dispersion process, the dust container was placed at the top so that the dust-air would flow downward along the dispersion tube to be discharged into the explosion vessel. To permit a more even dust distribution along the length of the tube, the diameter of the dispersion holes in the middle have been slightly enlarged compared to that at the ends.

Since the turbulence created by the dust dispersion jets decays rapidly with time, the turbulence level in the dust mixture during combustion can be controlled by varying the time delay between dispersion and ignition. Additional turbulence can also be introduced via another series of air jets emitting from small holes drilled along the length of another tube (identical to the dust dispersion tube) placed on the opposite wall. The turbulence tube was also 14 mm diameter and 910 mm long connected to a larger air reservoir (1500 cm^3) through another solenoid value. Four series of small VALVE holes were drilled along the length of this turbulence tube ranging in diameter from 0.5 to 1 mm. The four lines of holes were 30° apart as shown in Fig. 1. The time interval between the switching of the dust dispersion tube and the turbulence tube can be varied to control the turbulence in the system during combustion. No attempt at this stage has been made to measure the turbulence in the system. The turbulence intensity was assessed qualitatively from the pressure in the air reservoir (or the time delay between dispersion and ignition). For reasons of convenience, commercially available cornstarch was chosen as the fuel in the present investigation. Analysis of the cornstarch indicated a consistent mean particle size of 15 μm with a variance of approximately ±5 μm. The cornstarch AN was put in a oven at 70°C for thorough drying perior to use and a few PRIOR percent of a fluidizing agent (Cab-O-Sil) was added to enhance the dust dispersion process.

Ignition of the dust-air mixture was achieved by a black powder igniter. Typically, a 0.6 gm charge of black powder, contained inside a paper capsule, was "blown up" via a thin fuse wire connected directly to a 110 AC line. Diagnostics consisted almost entirely of pressure-time measurements inside the tube by a quartz piezoelectric transducer (PCB113A24, 5 mv/psi nominal). Although ionization probes were also placed along the length of the explosion tube to measure the time of arrival of the combustion "front", these data cannot be interpreted reliably until the structure and the thickness of the turbulent dust flame are better understood. Thus the pressure-time curve remains the principal diagnostic technique in the present study.

Since homogeneous gas flames are much better understood, it seemed appropriate to carry out some CH_4-air explosions in the same apparatus under the same turbulence conditions as a basis for comparison. In these methane explosion experiments the mixtures were premixed in the tube and the air reservoirs prior to the discharge into the explosion tube. Thus there was no mixing in the chamber as in the case of the heterogeneous dust-air mixture.

3. Classical Theory of Constant Volume Explosion

SIMILAR

Since the propagation of homogeneous gas flames in closed vessels is well understood, the natural tendency is to assume that the phenomenon is sijilar for the case of dust flames. It is tempting to derive a burning velocity for dust-air mixture from the pressure-time curve using the standard theory for constant volume explosion. Given a pressure-time curve, one can always assume a propagating combustion front progressively releasing energy and thereby pressurizing the vessel as is measured by the transducer. However, the pressure-time trace only represents progressive release of energy and without a propagating front, volumetric burning of the contents can give rise to a similar pressure-time trace. Thus the "burning velocity" derived from the $p(t)$ curve for dust explosion in a closed vessel may not correspond necessarily to a real flame front velocity of the dust mixture. Accordingly we shall use the dp/dt to represent a burning rate of the dust in the vessel and proceed to deduce the influence of turbulence on this burning rate in the particular vessel concerned. It should also be pointed out that the dp/dt chosen is a representative dp/dt from the $p(t)$ trace obtained. It is neither an averaged value nor the maximum. If we take the maximum,

then local fluctuations have to be considered and we feel that we do not understand sufficiently the combustion process inside to interpret the local phenomenon. On the other hand, if an average value is used then we would have to take a number of values of $\mathrm{d}p/\mathrm{d}t$ along the $p(t)$ curve. This we feel would de-emphasize the dominant processes. By representative value, we look at the $p(t)$ curve globally and assess a value of $\mathrm{d}p/\mathrm{d}t$ which is representative of the overall burning rate. Fig 2 shows a series of typical 993
$p(t)$ curves and the manner in which we choose the representative value for the burning rate.

Irrespective of whether a real thin propagating front exists or not, it is worthwhile to model the $p(t)$ curve obtained by such an idealized picture to provide a basis for interpreting the data obtained under different conditions. The theory for constant volume explosion has been considered by numerous investigators in the past [3, 4]. For our purpose, it is not necessary to be accurate and concerned with the details. Thus we shall only outline the essential features to get the important parametric dependence.

Consider a volume V filled with an explosive mixture with chemical 994
energy per unit mass Q. Assume the mixture to be perfect gas and assume an average constant value of the specific heat ratio γ for the burnt and unburnt gases. The internal energy of the volume is given by $U = MC_v T = MRT/\gamma - 1 = PV/\gamma - 1$ where T is an averaged temperature of the entire mass inside the volume V. Thus the rate of inside of internal energy of the volume is

INCREASE

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \frac{1}{\gamma - 1} V \frac{\mathrm{d}p}{\mathrm{d}t}$$

and assuming the energy release to be effected by some fictitious (or real) propagating combustion front at a velocity S relative to the gas ahead of it, we amy write 995

MAY

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \frac{V}{\gamma - 1} \frac{\mathrm{d}p}{\mathrm{d}t} = AS\varrho Q$$

where ϱ is the gas shead of the front. Assuming isentropic compression of the gas in the vessel, we write $\varrho = \varrho_0 \left(\frac{p}{p_0}\right)^{1/\gamma}$ and note that $\varrho_0 Q = \frac{MQ}{V}$

AHEAD

and $MQ = \frac{V}{\gamma - 1} \Delta p_{\max}$ we get

$$\frac{V}{\gamma - 1} \frac{\mathrm{d}p}{\mathrm{d}t} = AS \left(\frac{p}{p_0}\right)^{1/\gamma} \frac{\Delta p_{\max}}{\gamma - 1}$$

$$\left(\frac{V}{A}\right) \frac{\mathrm{d}p}{\mathrm{d}t} = S\, \Delta p_{\max} \left(\frac{p}{p_0}\right)^{1/\gamma}. \qquad (1)$$ 996

The area A of the combustion front is proportional to the volume $V^{2/3}$ thus the left hand side may be written as $\frac{V^{1/3}}{C} \frac{\mathrm{d}p}{\mathrm{d}t}$ where C is some constant of proportionality. The rate of pressure rise depends on the local pressure p, for the maximum rate of pressure rise $p = p_{\max}$ and

$$\mathrm{K}_{St} = V^{1/3} \left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)_{\max} = CS\, \Delta p_{\max} \left(\frac{p_{\max}}{p_0}\right)^{1/\gamma} \qquad (1.a)$$

The maximum pressure rise is a function of the energetics of the mixture (ie. Q) and for a given mixture, the left hand side is proportional to the burning velocity S. If the burning velocity is a property of the mixture (and not the turbulence) then the right hand side is constant giving the so called cubic law

$$V^{1/3}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)_{max} = \mathrm{K}_{St} = \text{constant}$$

The validity of the cubic law is thus clear. It requires that the burning velocity S depend only on the chemical properties of the mixture and not on the fluid dynamic states (ie. turbulence). Furthermore, it requires that the maximum pressure rise be dependent only on the properties of the mixture. For homogeneous gas mixtures, the constant volume explosion pressure is a function of the energetics. There may be a small dependence of Δp_{max} on the burning rate due to heat losses to the vessel walls in certain geometries. However, for heterogeneous dust mixtures, Δp_{max} would be more sensitive to the burning rate. This is due to fact that because of gravity settling of the dust, the total amount burned (hence Δp_{max}) would depend on the burning rate. Also, for more intense combustion (higher burning rates) the combustion mechanisms may be different in a dust mixture since heat and mass transfer rates to the individual particles control somewhat the chemical processes. It is fortuitous to expect that the cubic law be valid for dust mixtures. Nevertheless, it provides a basis to interpret results from different vessels by looking at the deviation from this ideal case.

Zam 583 Arch Comb. A.W. str. 56

szp. 20

Eq 1 can also be used to provide a basis for correlating results under various conditions. In general, different apparatus, different dispersion systems, turbulence level, types of dust, dust concentration, etc give widely different values for the $(\mathrm{d}p/\mathrm{d}t)_{max}$ and the Δp_{max}. However, these two common parameters, measured in almost all dust explosion experiments can be correlated using Eq. 1. There are nomerous reasons to argue that $(\mathrm{d}p/\mathrm{d}t)_{max}$ has no relationship with Δp_{max} at all. However, by studying the departure of the experimental data with the correlation provided by Eq. 1 permits different results to be analyzed. We shall attempt to explore the correlation (or non--correlation) of the present experimental data on the basis of the idealized framework provided by Eq. 1. It should be noted in a more formal analysis of thin flame propagation in closed bombs, and the mass inside is divided into two zones, burnt and unburnt gases with the front as the boundary, the more exact equation for the rate of pressure rise is given by

DATA

$$\left(\frac{V}{A}\right)\frac{\mathrm{d}p}{\mathrm{d}t} = S\,\Delta p_{max}\left(\frac{\Delta p}{p_0}+1\right)^{1/\gamma_u}\left\{1-\left(1-\frac{\Delta p}{\Delta p_{max}}\right)\left(\frac{p_0}{\Delta p+p_0}\right)^{1/\gamma_u}\right\}^{2/3} \qquad (1.b)$$

where γ_u is the γ of the unburned mixture. Kauffman et al. [5] have derived a $(\mathrm{d}p/\mathrm{d}t)$ relationship for thick flames. However, the expression involves additional unknown parameters such as the flame thickness. In closed bomb combustion, it is not clear if a discrete burning zone exists. It is therefore felt that the simplest relationship is sufficient for the present and is more compatible with our knowledge of the dust combustion phenomenon itself.

Based on the simplest form of the theoretical result (ie. Eq. 1), the value of $\frac{1}{S}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)$ is plotted against Δp_{max} in Fig. 3. A range of arbitrary values of burning velocity between $0.5 < S < 5$ m/s is plotted. Corresponding to this range of "S", the values for $\frac{1}{S}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)$ vary over an order of magnitude also as indicated by the direct proportionality between the rate of pressure rise and the burning velocity S. In Eq. 1, we note that the rate of pressure rise depends on the local pressure Δp in the vessel with the maximum (dp/dt) occuring at $\Delta p = \Delta p_{max}$. Taking $\Delta p = 0.5\,\Delta p_{max}$ the case for $S = 0.5$ m/s is also plotted in Fig. 3 to show the dependence on Δp. For the present purposes, it suffices to take the maximum value for $(dp/dt)_{max}$ for the purposes of qualitative comparison with experiments. It should be noted that in Eq. 1, 1a, 1b, the specific properties of the explosive mixture inside the vessel do not enter explicitly into the equation, except perhaps through the value of the specific heat ratio γ which is a weak dependence. Thus it is a general expression which should be valid for all mixtures. The influence of turbulence enters through the value of the burning velocity S. Given an experimental pressure-time curve, it is always possible to use Eq. 1, 1a, or 1b to derive a burning velocity S. However, this value of S derived may not necessarily have any physical significance in that it does not correspond to any experimentally measured burning velocity. Of course for gas mixtures where S can be found from independent experiments as a function of p and T, it can also be used in Eq. 1 to calculate a $(dp/dt)_{max}$. In this case, direct comparison between theory and experiment is meaningful.

4. Results and Discussion

Inherent in the generation of any dust-air cloud is the obvious requirement of a dust dispersion process which usually involves considerable turbulence per se to achieve a uniform dust suspension in the experimental vessel. It seems natural, therefore, that in any study of the influence of turbulence on dust explosion, it is first essential to assess the effect of the dispersion process itself on the combustion rate. To this end a series of experiments were performed to establish systematically the dependence of the burning rate on the parameters of the dispersion process alone. The results are summarized in Figs. 4 through 7. The variables in the combustion-dispersion process for a given dust concentration are the initial pressure in the dispersion discharge vessel and the delay time between dispersion and ignition. The initial pressure in the discharge vessel controls the initial intensity of the dispersion turbulence. The time delay between dispersion and ignition reflects the residual turbulence level at the time of ignition. It can be expected that the decay of the turbulence intensity is quite rapid in the dispersion jets emanating from the small holes.

Fig. 4 shows the variation of $(dp/dt)_{max}$ with the time delay between dispersion and ignition. Results for three different dispersion pressures are shown together. In all cases, the discharge time of the compressed air from the dispersion bottle is about 100 msec. The general trend is clear: for short delay times, the values for $(dp/dt)_{max}$ are quite high. Although there is a large scatter of the results, one can also note that the high values of $(dp/dt)_{max}$ correspond to high pressures in the dispersion bottle.

Thus the influence of turbulence intensity on the overall burning rate is evident. For delay times larger than the ust dispersion time of about 100 ms, DUST the $(dp/dt)_{max}$ drops sharply indicating the rapid decay rate of the dispersion turbulence. In the present dispersion system, the scale of the turbulence is quite small, typically of the order of the diameter of the disperion jet hole of about 1 mm. In the Hartmann-type of dispersion system where the dust is blown from a cup by an air blast, the scale of turbulence is much larger and thus a slower decay rate is observed. For delay times larger than the dispersion time, all the three cases show similar results. The corresponding case of Δp_{max} with delay time is displayed in Fig. 5. Again for short delay times and high levels of turbulence, very large fluctuations in Δp_{max} are observed. The variation of Δp_{max} with delay time (ie. turbulence intensity) is less sensitive than for $(dp/dt)_{max}$ which relates to the burning rate. The decrease in Δp_{max} with delay time could be due to the settling out of the dust suspension as the turbulence intensity dimishes. Large fluctuations in Δp_{max} for short delay times and high turbulence intensities could be due to the quenching effect of turbulence. It should be noted that although the same amount of dust is used each time (ie. ~ 12 gm) the actual amount of dust dispersed depends to some extent on the dispersion pressure. The values given in the table accompanying Figs. 4 and 5 are obtained by weighing the dust left in the dispersion system after an experiment. In general, a higher dispersion pressure gives a more effective convection of the dust out to the combustion tube through the jet orifices.

Fig. 6 shows the variation of $(dp/dt)_{max}$ with the delay time. A dispersion bottle pressure of 10 atm is used throughout. For the different dust concentrations, peak values of $(dp/dt)_{max}$ are obtained at a delay time of about 75 ms. It should be noted that the total dispersion time is about 100 ms. For too short a delay, insufficient dust has been released into the chamber to give a strong initial flame kernel for rapid subsequent flame propagation. About 75 ms appears to be a reasonable time for optimum conditions since most of the dust has been released and the turbulence level has not decayed as yet. The $(dp/dt)_{max}$ drops rapidly with increasing delay time past 100 ms when the dispersion air has completely discharged and turbulence has started to decay rapidly. In general, the present results show a more rapid decay of $(dp/dt)_{max}$ with delay time than experiments using the Hartmann type of dispersion system. This is due to the fine scale turbulence in the present experiments and thus a more rapid decay rate from the jet dispersion system used. A general trend of higher burning rate with increasing dust concentration is illustrated in Fig. 6.

Fig 7 is the accompanying $(\Delta p)_{max}$ with delay time. Again peak values are observed at about 75 ms 100 ms corresponding to peak values of $(dp/dt)_{max}$. The decay of $(\Delta p)_{max}$ with increasing delay time (hence decreasing turbulence intensity) is much less severe than the decay for $(dp/dt)_{max}$. There is a strong indication of dust settling since for higher dust concentrations the decay is much more rapid. For high dust concentration it is suspected that the dust does not get broken up properly when it is convected with the air from the dust chamber through the dispersion tube and out through the jet orifices. Thus the dust discharged into the chamber is probably in large agglomerated "chunks" and hence settles more rapidly. For the lean concentration cases (eg. the 7 gm case (lowest)) there is hardly any decay in the $(\Delta p)_{max}$ with delay. For 7 gm dust, the air blast fully breaks up the dust and a fine dust suspension is most likely achieved. The settling of the dust if it is in the form of its nominal particle size of out 15 μm without ABOUT agglomeration will settle slowly and thus the amount burned is practically independent of the delay time or turbulence level. This is reflected in Fig. 6 also where the $(dp/dt)_{max}$ also demonstrates negligible decay with delay time

SLOWLY

for the lean concentration case. The results strongly suggest that the role of turbulence in suspending the dust so that it can be burned is perhaps more important than the role it plays in influencing the burning rate via more rapid heat and mass transport rates in the burning zones.

It would be of interest to compare the $(dp/dt)_{max}$ and $(\Delta p)_{max}$ data from the present experimental study with those of others [5–9]. It should be borne in mind that the particle size and other properties of the cornstarch used by other investigators would generally be different. Also more importantly the dispersion and distribution of the dust, the turbulence intensity, as well as the losses from the different experiments can be expected to differ drastically for a meaningful quantitative comparison. Nevertheless, from a global point of view such a comparison does provide a qualitative measure of the scatter and represents the accuracy of the available explosion data for dust. Fig. 8 shows the variation of Δp_{max} with dust concentration. The present data should be compared first with the data from a spherical bomb of 0.333 m^3 and from a cylindrical bomb of 0.180 m^3 and an $L/D \simeq$ $\simeq 1$ which were obtained previously at McGill using the same cornstarch and with the same drying procedures before use [9]. As can be observed, the Δp_{max} data all from the same laboratory with the same dust show quite good agreement. The present data is slightly lower than the data from the spherical and the cylindrical vessels suggesting that heat losses to the walls are perhaps more significant in the present apparatus since the L/D ratio is much higher. Hartmann's data [7] is unusually high perhaps

due to the high energy levels in his ignition source used and the small volume of the Hartmann bomb of 0.0123 m^3. Kauffman's data [5] are from a 1 m^3 bomb with two levels of turbulent intensities (ie. $u' = 1.5$ and 4.2 m/s). The Δp_{max} corresponding to a higher turbulence level could again be due to the better break up of the dust particles by high shear rate, better suspension and less rapid settling when the dust is in the form of its original particle size, rather than in large agglomerate "chunks". Fig. 9 shows the corresponding $K_{St} = (dp/dt)_{max} \cdot V^{1/3}$ from the different investigators. As expected, the scatter of the K_{St} factor is much larger than that of the $(\Delta p)_{max}$. It is difficult to find a representative value of the K_{St} factor for corn starch from the wide scatter f the data shown. It is however possible if one adopts a particular dispersion method, vessel size and geometry to produce reproducible K_{St} values from the same vessel for different dusts may provide a meaningful basis for comparison of the explosivity for different dusts. However, it is difficult to provide a more fundamental interpretation of the K_{St} factor

OF

FROM A SIMPLISTIC

Plistic point of view the (dp/dt) represents an energy release rate (or burning rate) inside the closed vessel. Even though there may or may not be a discrete flame front propagating from the ignition source to consume the entire dust mixture, the simple theory of constant volume combustion does provide a correlation between the K_{St} and Δp_{max} (as given by Eq. 1). In Eq. 1, the burning velocity S should be considered as a parameter which may or may not necessarily correspond to an experimentally measurable burning velocity. It is of interest to test the present data against the correlation given by Eq. 1 and since the data from the same vessel is used, $(dp/dt)_{max}$ is used instead of the K_{ST} factor plotted against Δp_{max} [illegible] in Fig. 10. It shoudl be noted that the points represent different concentrations, different dispersion pressures, as well as small variations in the arrangement of the dispersion jets. Nevertheless, the data all fall within a band bounded by the parameter S between 0.5 m/s and 2 m/s.

DELETE

SHOULD

FINE DUST

If S is to be interpreted formally as a turbulent burning velocity, then within the range of turbulence level of the present experiment, a much wider variation is expected. The correlation in Fig. 10 suggests that turbulence perhaps plays a more important role in breaking up the dust by higher shear rate and better distribution of the ine dist particles, preventing rapid sedimentation than in the augmentation of the turbulent burning velocity. This is reasonable from the point of view that turbulence can easily quench a dust flame in comparison with a gas flame where the flame thickness is expected to be much smaller. If turbulence does not play a strong role in controlling the burning velocity parameter "S" for dust, then one would expect the correlation of $(dp/dt)_{max}$ with Δp_{max} as given by Eq. 1 to be a fair representation of the data as indicated by Fig 10. To compare with the $(dp/dt)_{max}$ from other experimental apparatus, the K_{St} must be used to scale the vessel size. Fig. 11 shows the variation of the K_{St} with Δp_{max} from different investigators. As expected, the scatter is much larger. As with Fig. 9 for the $(dp/dt)_{max}$ it is difficult to accout for the differences between different experiments due to the large number of parameters involved in dust explosion.

ACCOUN

5. Concluding Remarks

THAT

Dust combustion is a complex phenomenon. It is felt that there is insufficient knowledge of the fundamental mechanisms of flame propagation in a dust mixture to properly assess the role played by turbulence. While there is no doubt hat in certain mixtures, the flame can be sufficiently thin to permit concepts from gas flame to be used in the interpretation of the result for dust-air flames, these concepts are not valid in general. The concept of a burning velocity requires the existence of a well-defined flame zone. This may not be attained for dust flames in general. Although a propagating front boundary may be defined, an equilibrium real boundary where combustion terminates may not necessarily exist, particularly in small closed vessels. Direst measurement of the velocity of the front boundary and dividing by the estimated density ratio may not represent a meaningful burning velocity. On the other hand, a (dp/dt) can always be measured in closed volume combustion irrespective of the fact whether or not a burning velocity can be defined meaningfully. The $(dp/dt)_{max}$ does represent a burning rate characteristic of the mixture and its turbulence level. It is felt that it is more meaningful to explore the $(dp/dt)_{max}$ at this stage than to proceed further to more basic levels involving the burning velocity since assumptions, not necessarily justifiable in general, have to be invoked. Perhaps most significant is that the present results suggest that the role of turbulence is more important in breaking up the dust and provide a finer suspension with slower sedimentation rate than in the augmentation of the burning rate via increased heat and mass transport rates.

6. References

[1] BARTKNECHT W.: *Explosion-Course-Prevention-Protection*. Springer-Verlag, New York, 1980

[2] ECKHOFF R. K.: The First International Colloquium on Explosibility of Industrial Dust in Baranow, Poland, November 8–10, 1984

[3] BRADLEY D. and MITCHESON A.: Combustion and Flame, 26, 201–217 (1976)

[4] NAGY J. and VERAKIS C.: *Development and Control of Dust Explosions*. Marcel Dekker Inc., New York and Basel, 1985 993

[5] KAUFFMAN C. W., SRINATH S. R., TEZOK F. I., NICHOLLS J. A. and SICHEL M.: 20th International Symposium on Combustion

[6] COCKS ~~R. E. and~~ Mayer R. C.: *Fabrication and use of a 20 liter spherical dust testing apparatus*. Process Specialities Section, Engineering Division, Procter and Gamble, Cincinnati, Ohio

CAP LETTERS

[7] HARTMANN I., COPPER A. R. and JACOBSON M.: U. S. Bureau of Mines, R. I. 4725, 1951

[8] NAGY J., SEILER E. C., CONN J. W. and VERAKIS H. C.: U. S. Bureau of Mines, R. I. 7507, 1975

[9] BOND J. F., KNYSTAUTAS R. and LEE J. H. S.: *Dybamics of Explosions*, Progress in Astronautics and Aeronautics, Vol. 106, pp. 571–584 (1986) 994

Received November 1986

Fig. 1. Schematic Diagram of the Experimental Apparatus

Fig. 2. Experimental Traces of the Variation of Pressure with Time

Fig. 3. Theoretical Model of Constant Volume Wxplosion-Variation of Scaled $(dp/dt)_{max}$ with $(\Delta p)_{max}$

Fig. 4. Experimental Results for the Variation of $(dp/dt)_{max}$ with Delay Time to Ignition at Different Dispersion Pressures

Fig. 5. Experimental Results for the Variation of $(\Delta p)_{max}$ with Delay Time to Ignition at Different Dispersion Pressures 995

Fig. 6. Experimental Results for the Variation of $(dp/dt)_{max}$ with Delay Time of Ignition at Different Dust Concentrations

Fig. 7. Experimental Results for the Variation of $(\Delta p)_{max}$ with Delay Time to Ignition at Different Dust Concentrations

Fig. 8. Comparison of Results for the Maximum Explosion Overpressure in Cornstarch-Air Mixtures as a Function of Concentration

●	Present Work	$V = 0.025\ m^3$ cylinder
▽	Bond et al. [9]	$V = 0.333\ m^3$ sphere
○	Bond et al. [9]	$V = 0.180\ m^3$ cylinder
○	Bond et al. [9]	$V = 0.180\ m^3$ cylinder
△	Cocks et al. [6]	$V = 0.02\ m^3$ sphere
	Hartmann et al. [7]	$V = 0.00123\ m^3$ cylinder
□	Nagy et al. [4]	$V = 0.00123\ m^3$ cylinder
	Kauffman et al. [5]	$V = 0.95\ m^3$ sphere

996

Fig. 9. Comparison of Results for the K_{ST} Factor in Cornstarch-Air Mixtures as a Function of Concentration

○	Present work	$V = 0.025\ m^3$ cylinder
	Bond et al. [9]	$V = 0.333\ m^3$ sphere
○	Bond et al. [9]	$V = 0.180\ m^3$ cylinder
○	Bond et al. [9]	$V = 0.180\ m^3$ cylinder
△	Cocks et al. [6]	$V = 0.02\ m^3$ sphere
	Hartmann et al. [7]	$V = 0.00123\ m^3$ cylinder
□	Nagy et al. [4]	$V = 0.00123\ m^3$ cylinder
●	Kauffman et al. [5]	$V = 0.95\ m^3$ sphere

997

Fig. 10. Experimental Results for the Variation of $(dp/dt)_{max}$ with Δp_{max} in the Present Study

Fig. 11. Comparison of Experimental Results for the Variation of the K_{ST} Factor with Δp_{max}

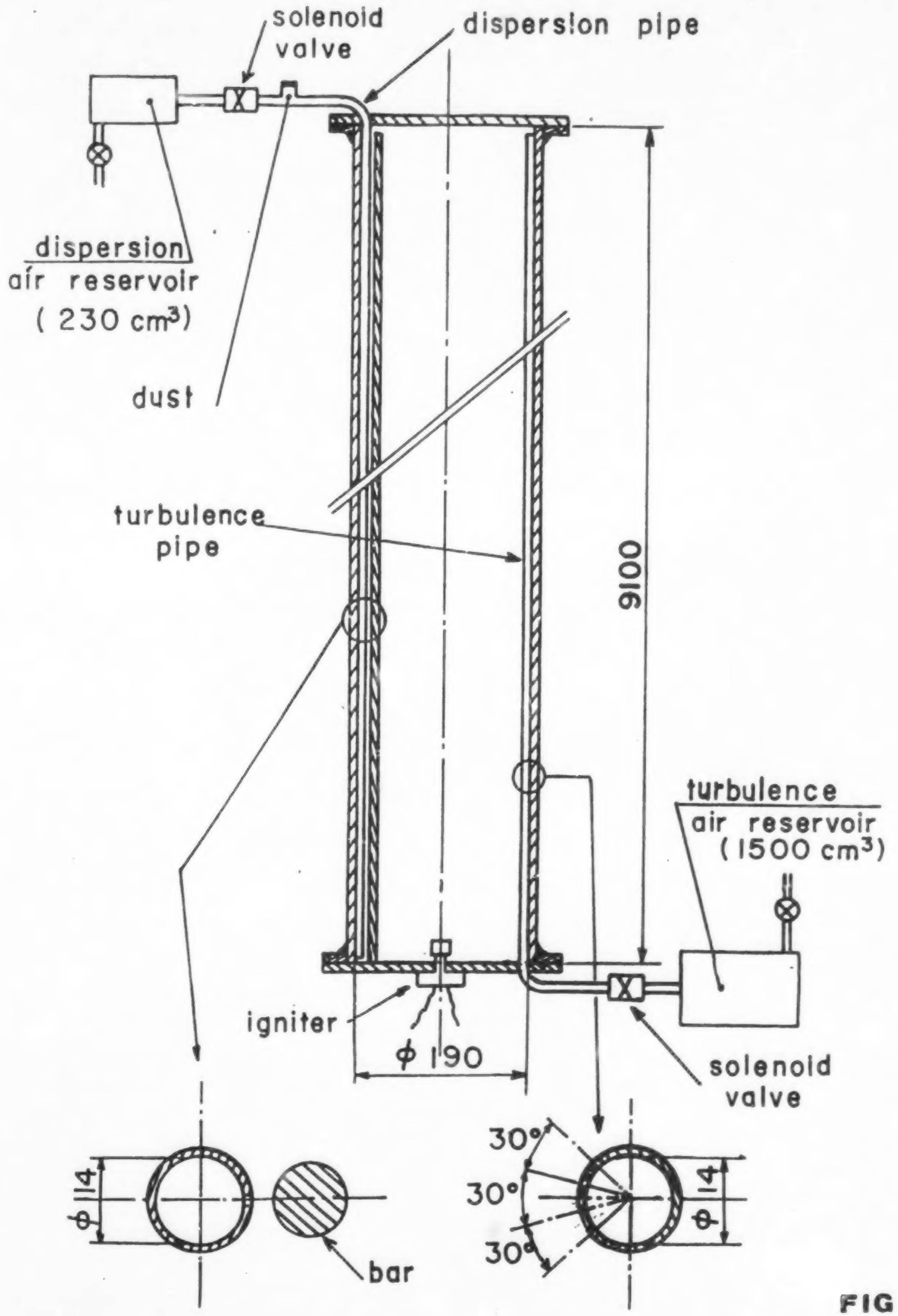

solenoid valve
dispersion pipe
dispersion air reservoir (230 cm³)
dust
turbulence pipe
9100
turbulence air reservoir (1500 cm³)
igniter
ϕ 190
solenoid valve
ϕ 114
bar
30°
30°
30°
ϕ 14

FIG · 1

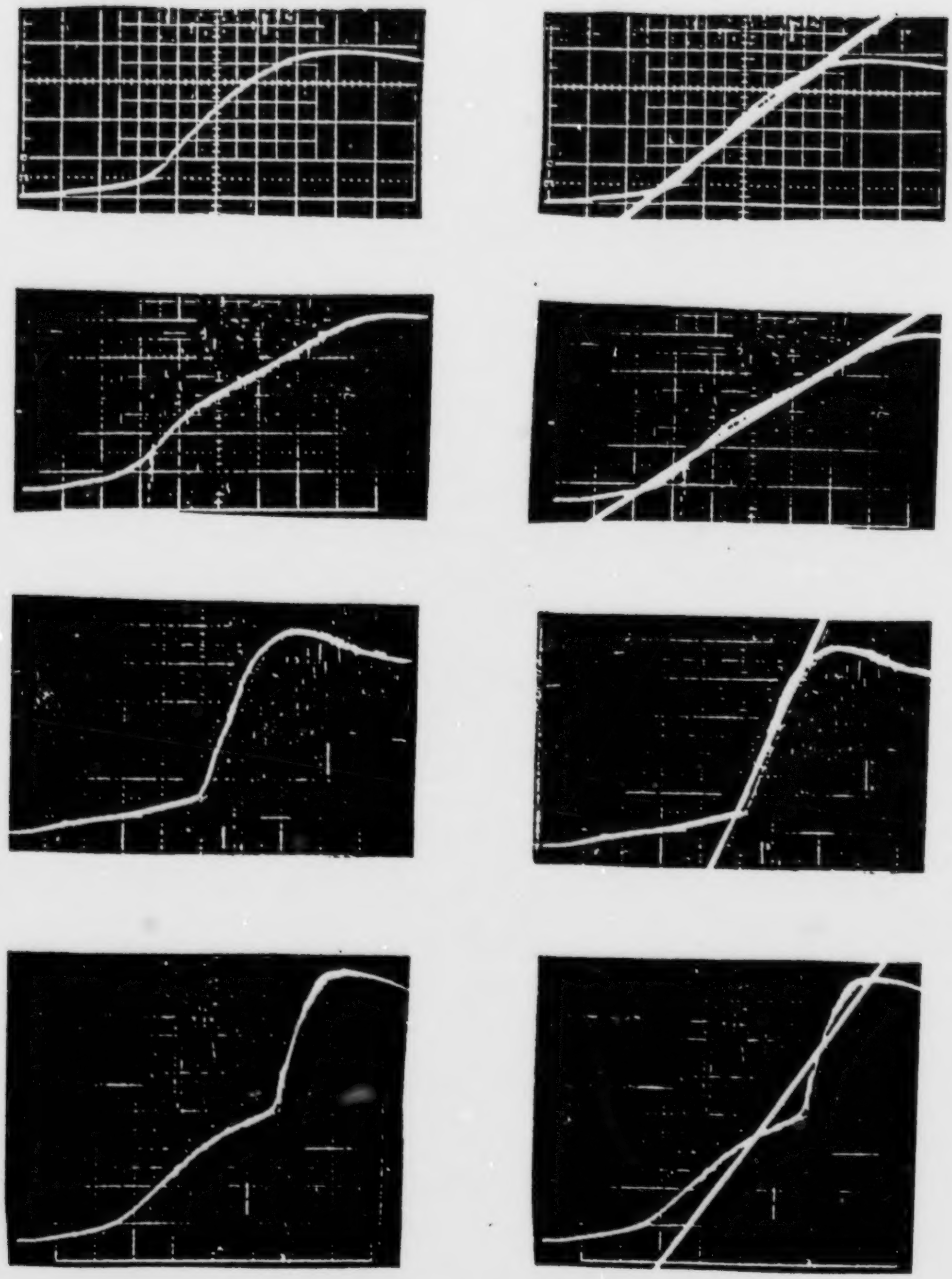


Fig. 2 Experimental Traces of the Variation of Pressure with Time

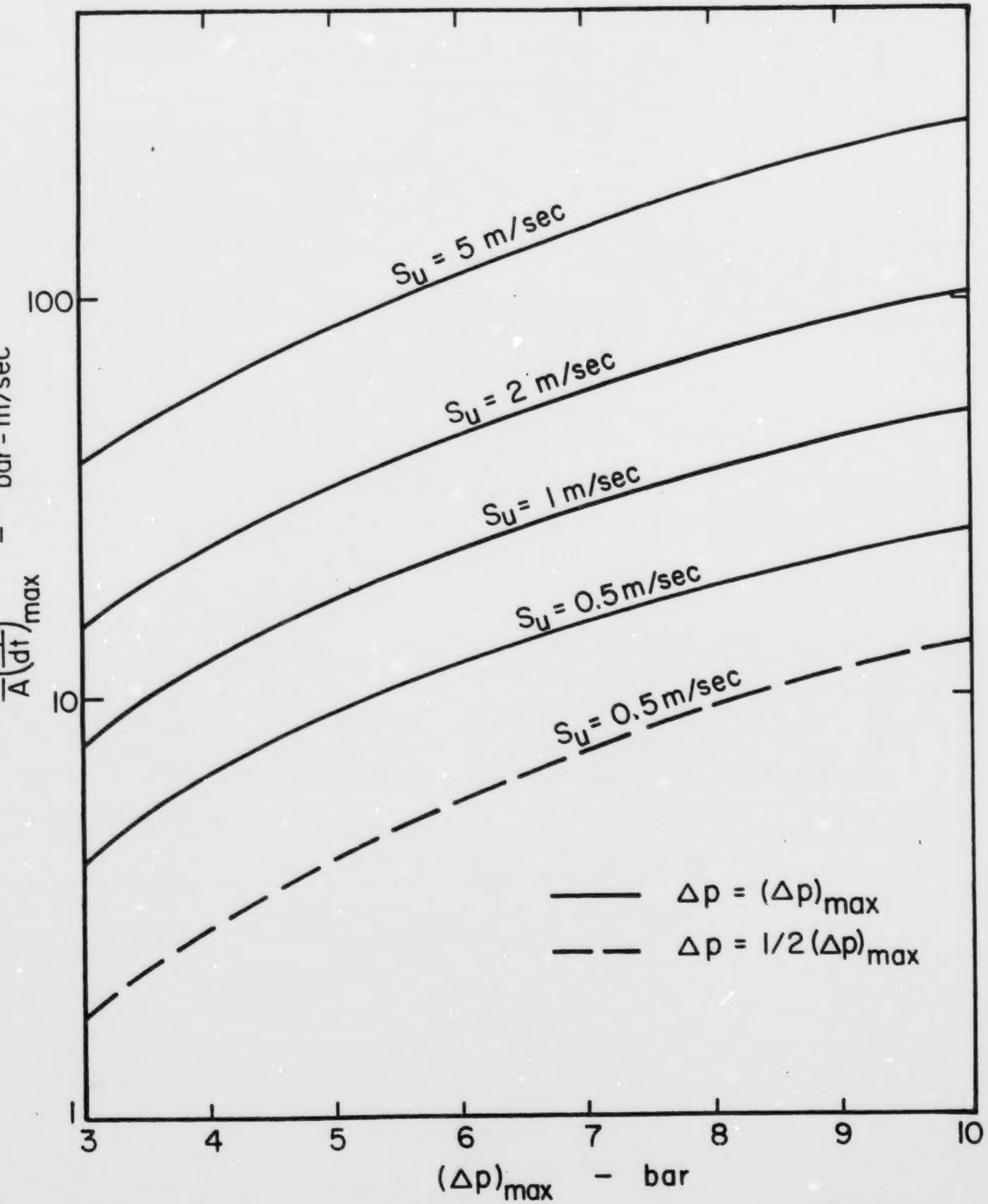
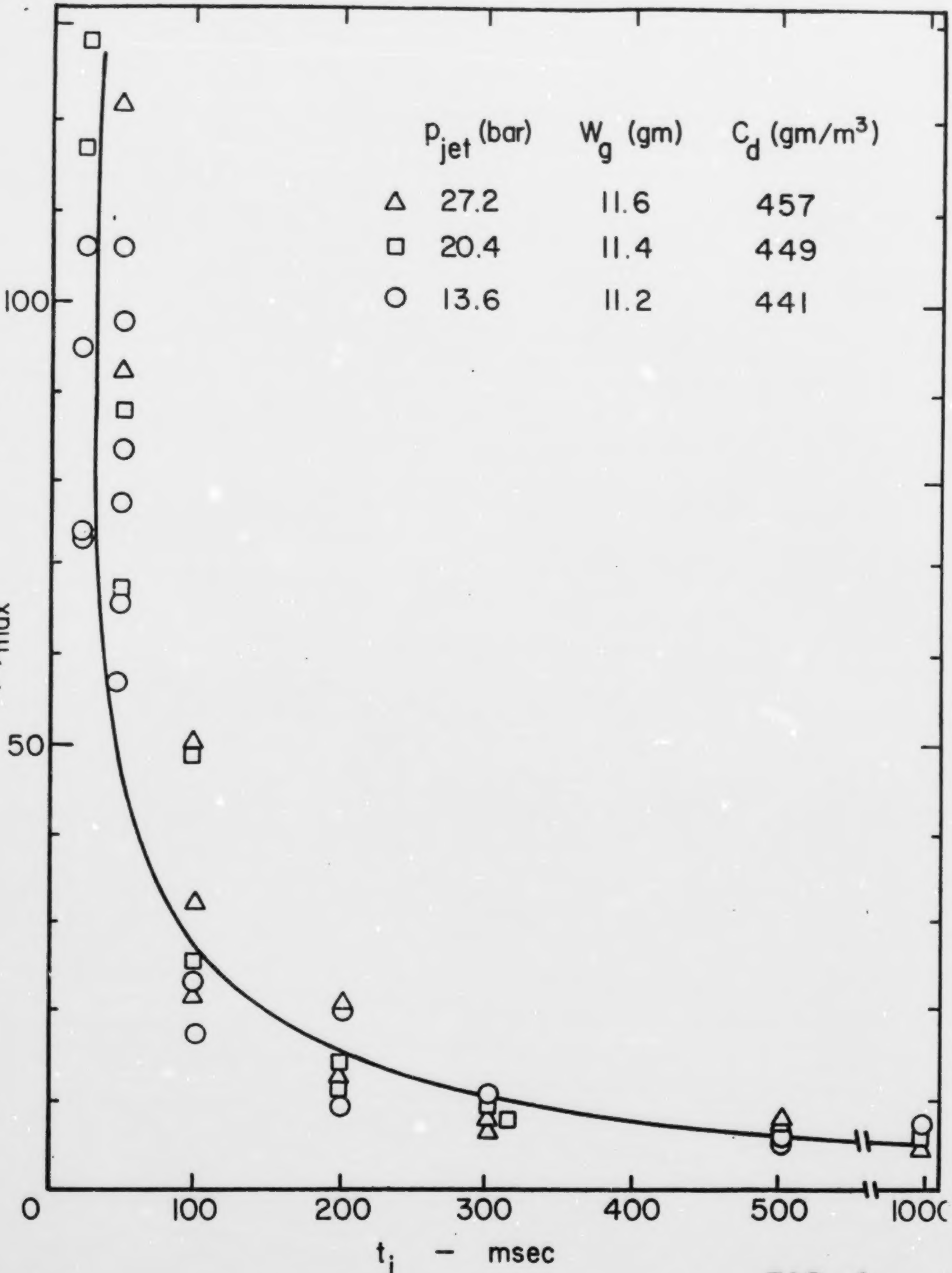
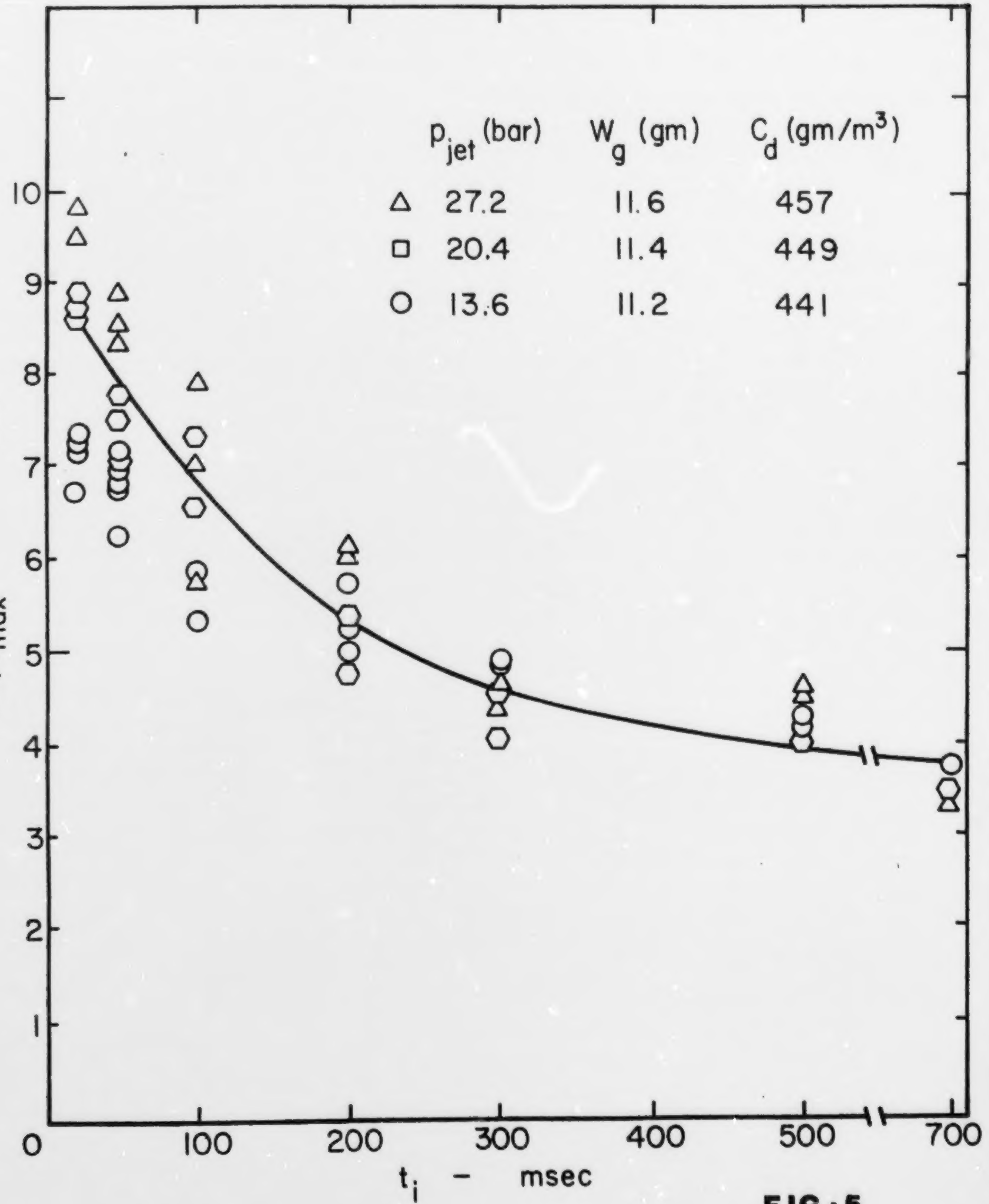
$\frac{V}{A}\left(\frac{dp}{dt}\right)_{max}$ - bar - m/sec
1
10
100
3
4
5
6
7
8
9
10
$(\Delta p)_{max}$ - bar
S_u = 5 m/sec
S_u = 2 m/sec
S_u = 1 m/sec
S_u = 0.5 m/sec
S_u = 0.5 m/sec
$\Delta p = (\Delta p)_{max}$
$\Delta p = 1/2\,(\Delta p)_{max}$

FIG. 3



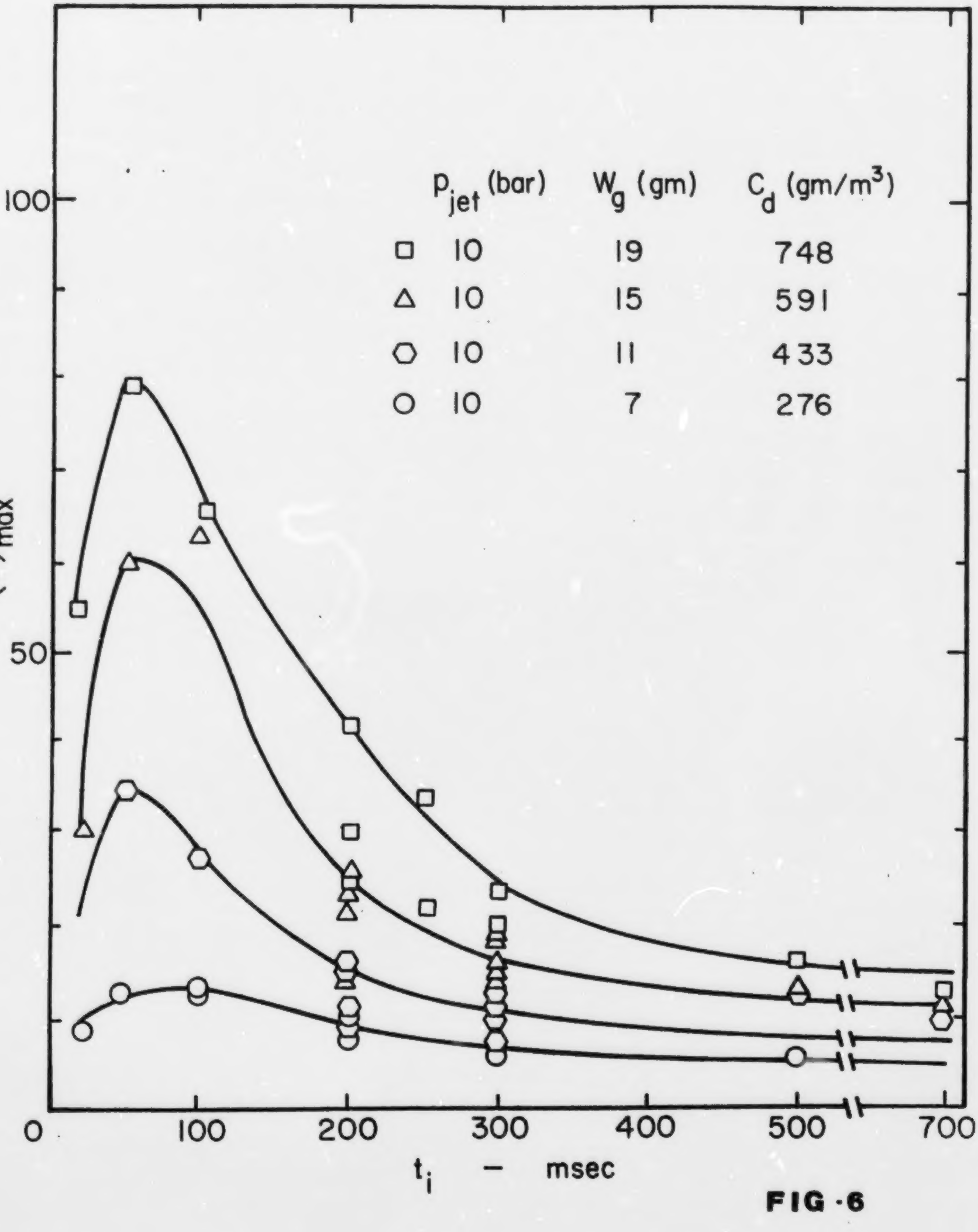
p_{jet} (bar)
W_g (gm)
C_d (gm/m^3)
△ 27.2 11.6 457
□ 20.4 11.4 449
○ 13.6 11.2 441
100
50
0
100
200
300
400
500
$\left(\frac{dp}{dt}\right)_{max}$ — bar/sec
t_i — msec

FIG · 4



p_{jet} (bar)
W_g (gm)
C_d (gm/m^3)
△ 27.2 11.6 457
□ 20.4 11.4 449
○ 13.6 11.2 441
$(\Delta p)_{max}$ – bar
t_i – msec
0
100
200
300
400
500
700
1
2
3
4
5
6
7
8
9
10

FIG·5



p_{jet} (bar)
W_g (gm)
C_d (gm/m^3)
□ 10 19 748
△ 10 15 591
⬡ 10 11 433
○ 10 7 276
100
50
0
$\left(\frac{dp}{dt}\right)_{max}$ — bar/sec
100
200
300
400
500
700
t_i — msec

FIG·6

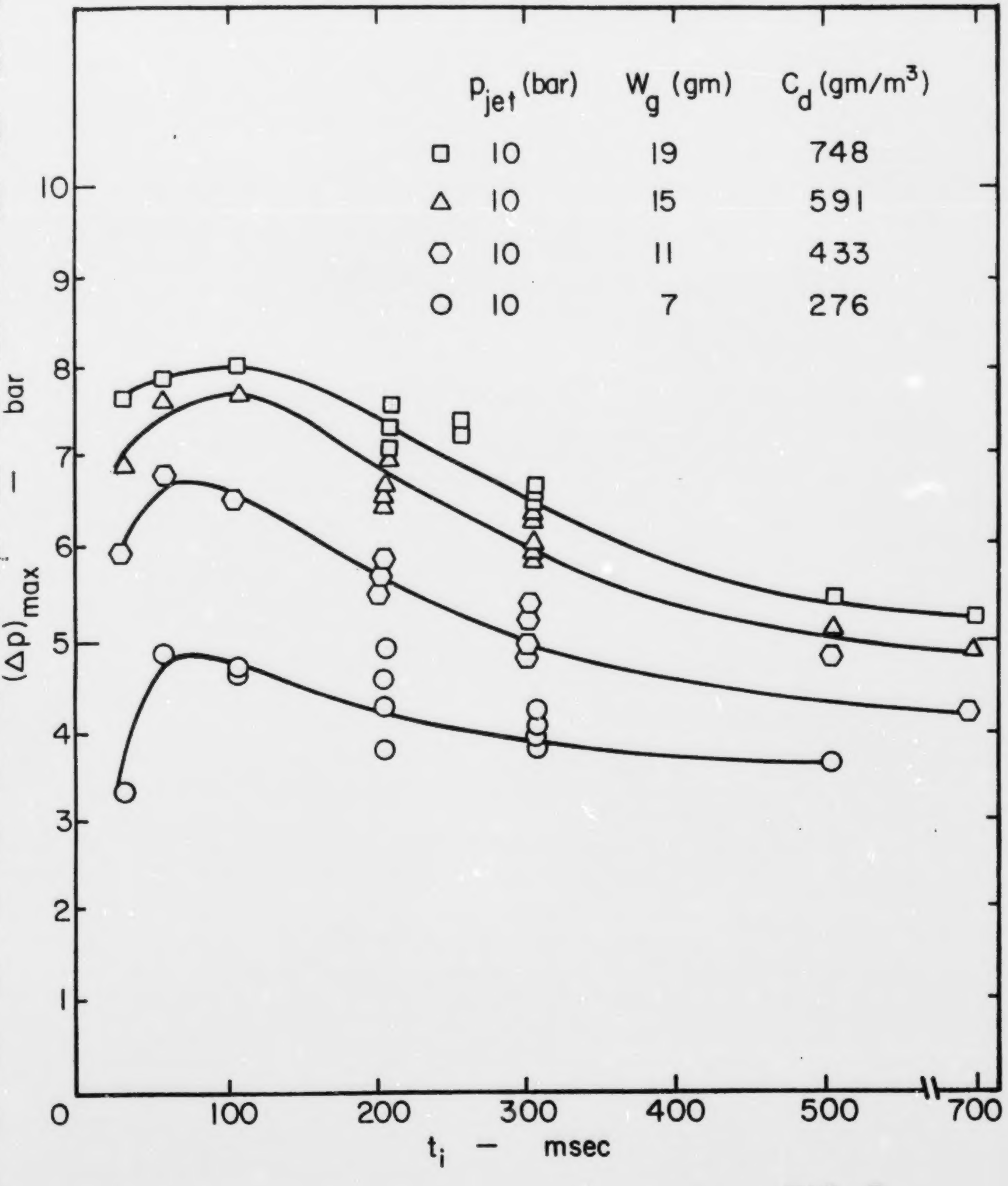

p_{jet} (bar) W_g (gm) C_d (gm/m^3)
□ 10 19 748
△ 10 15 591
⬡ 10 11 433
○ 10 7 276
$(\Delta p)_{max}$ — bar
t_i — msec
0
1
2
3
4
5
6
7
8
9
10
100
200
300
400
500
700

FIG · 7

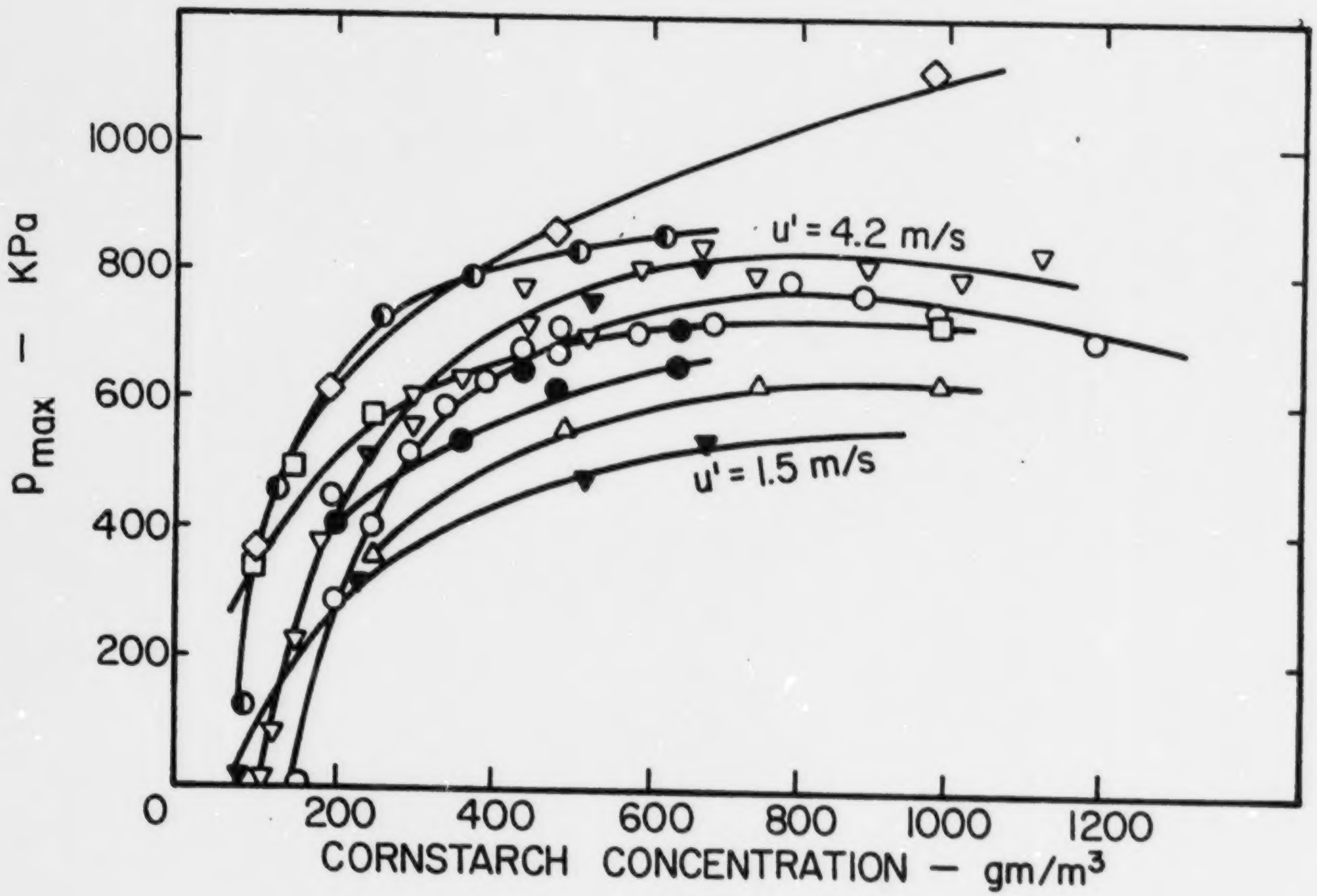

u' = 4.2 m/s
u' = 1.5 m/s
p_{max} — KPa
1000
800
600
400
200
0
200
400
600
800
1000
1200
CORNSTARCH CONCENTRATION — gm/m³

FIG · 8

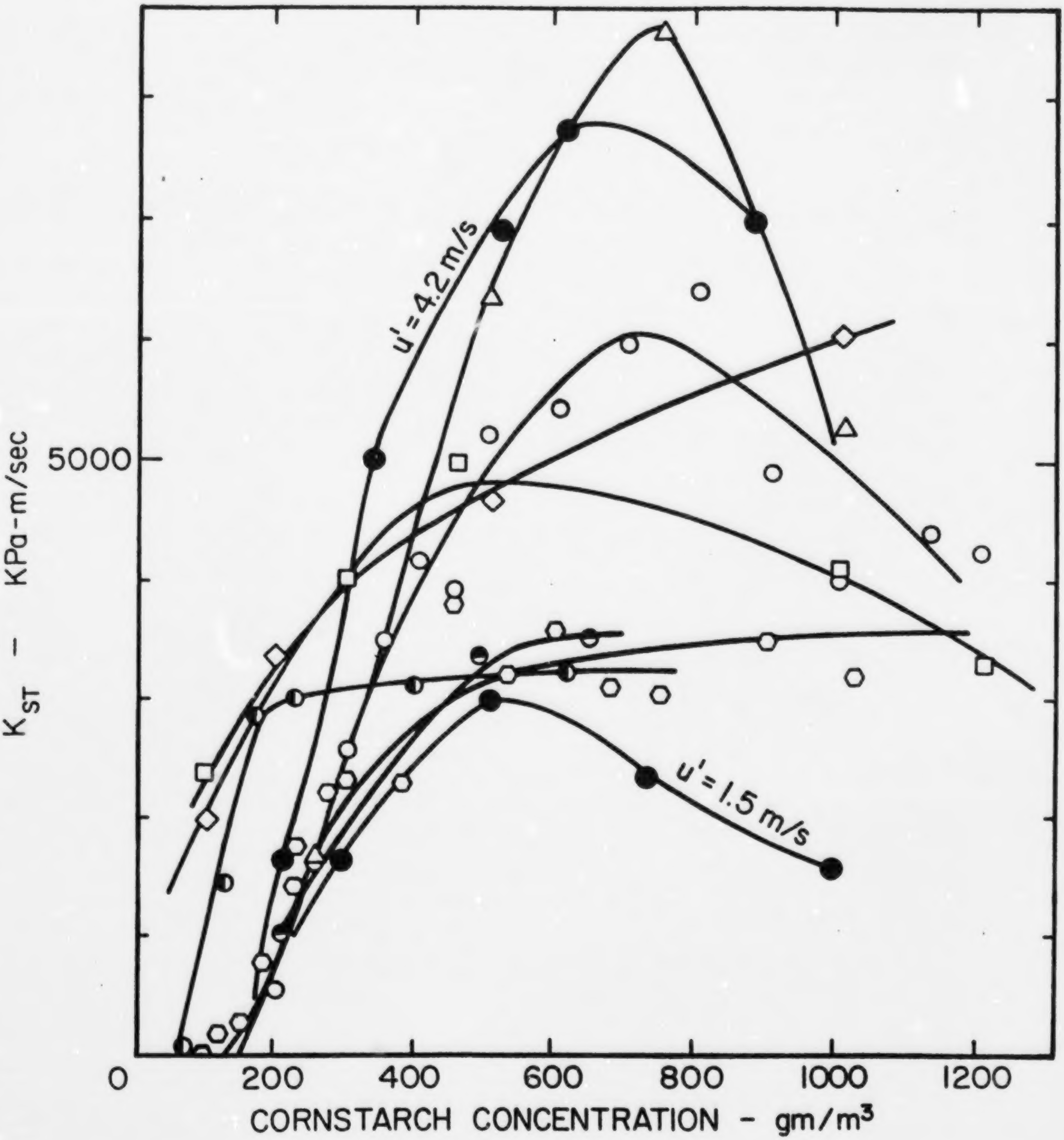
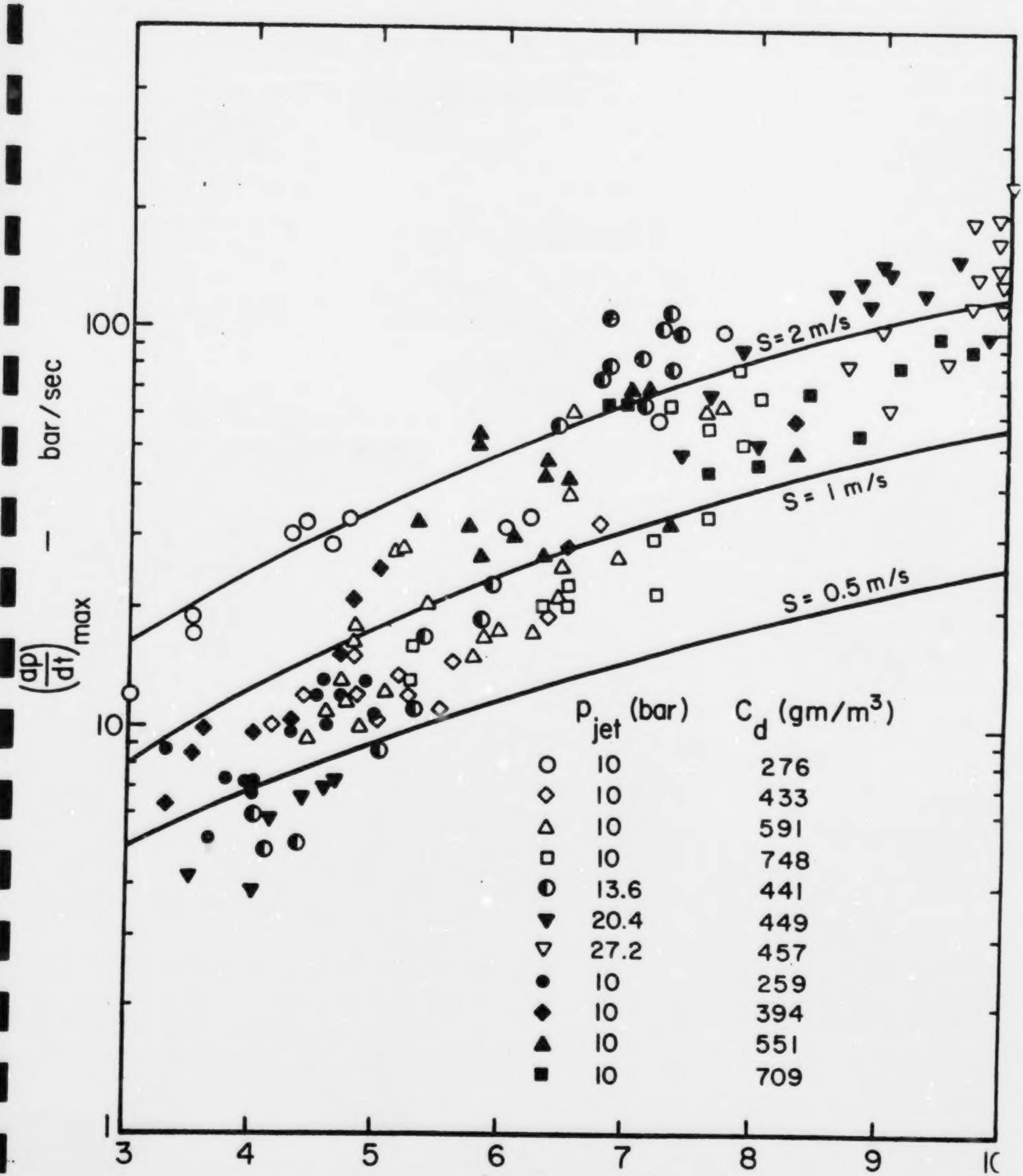
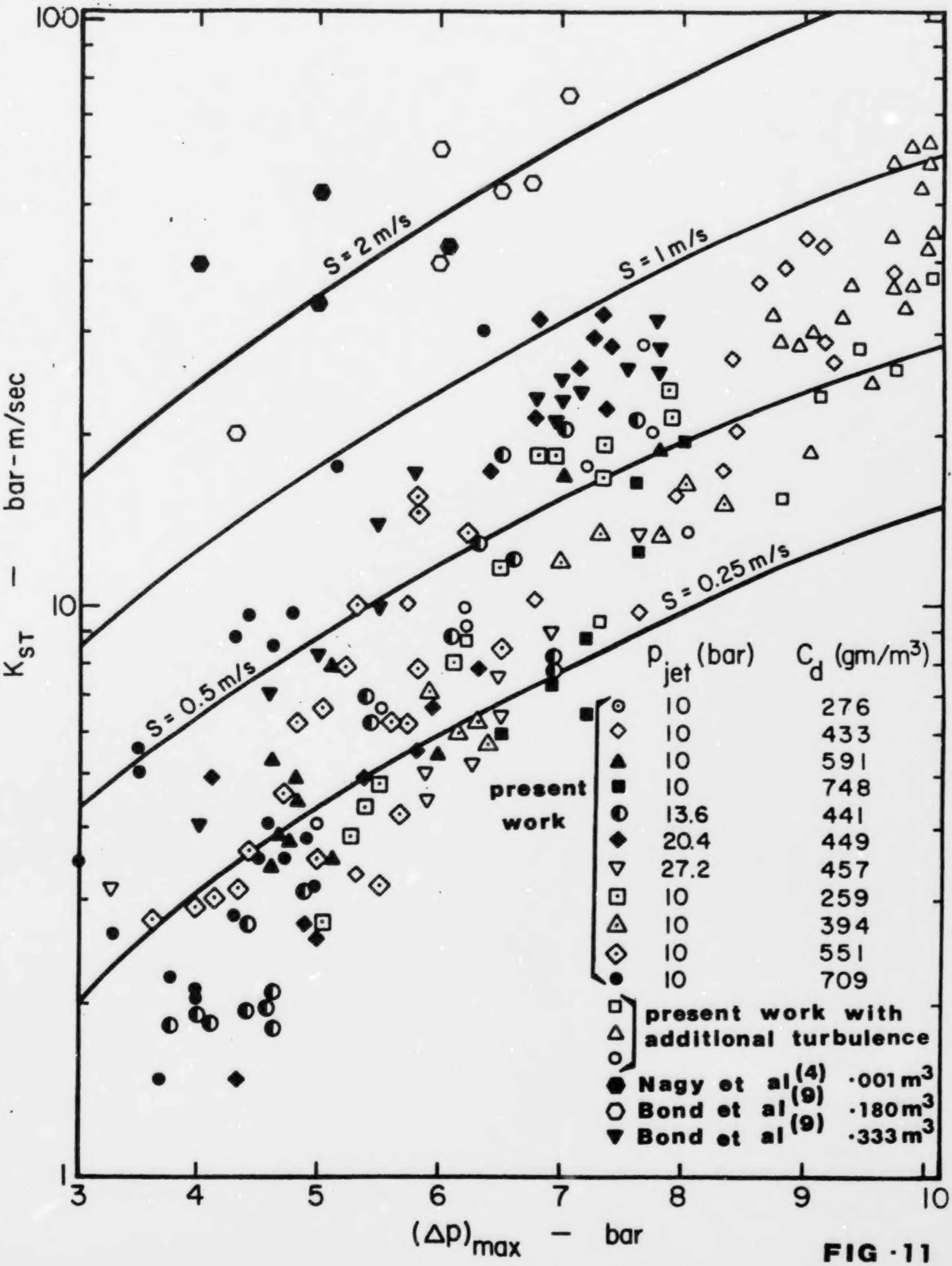

K_{ST} - KPa-m/sec
5000
0
200
400
600
800
1000
1200
CORNSTARCH CONCENTRATION - gm/m³
u' = 4.2 m/s
u' = 1.5 m/s

FIG ·9



$\left(\frac{dp}{dt}\right)_{max}$ — bar/sec
1
10
100
3
4
5
6
7
8
9
1(
$(\Delta p)_{max}$ — bar
S = 2 m/s
S = 1 m/s
S = 0.5 m/s
p_{jet} (bar)
C_d (gm/m^3)
○ 10 276
◇ 10 433
△ 10 591
□ 10 748
◐ 13.6 441
▼ 20.4 449
▽ 27.2 457
● 10 259
◆ 10 394
▲ 10 551
■ 10 709

FIG·10



K_{ST} — bar-m/sec
$(\Delta p)_{max}$ — bar
100
10
1
3
4
5
6
7
8
9
10
S = 2 m/s
S = 1 m/s
S = 0.5 m/s
S = 0.25 m/s
p_{jet} (bar) C_d (gm/m^3)
present work
⊙ 10 276
◇ 10 433
▲ 10 591
■ 10 748
◐ 13.6 441
◆ 20.4 449
▽ 27.2 457
⊡ 10 259
△ 10 394
◈ 10 551
● 10 709
□ △ ○ present work with additional turbulence
⬢ Nagy et al (4) ·001 m^3
⬡ Bond et al (9) ·180 m^3
▼ Bond et al (9) ·333 m^3

FIG ·11